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ANALYSIS OF RUNWAY ROUGHNESS

Prepared For

TRANSPORTATION DEVELOPMENT CENTRE
of the POLICY AND COORDINATION GROUP
&
AIRPORTS AUTHORITY GROUP
TRANSPORT CANADA

Prepared By

JOHN EMERY GEOTECHNICAL ENGINEERING LIMITED

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By

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16. Abstract

The purpose of this research project was to assess the state of current technology for collecting and analyzing longitudinal runway profiles in order to recommend a method(s) for Transport Canada use. Runway longitudinal profile data for five runways collected by Transport Canada using a Digital Incremental Profiler (Dipstick^{R}), in addition, four other runway profiles were analyzed. The three analysis methodologies selected were: Surface Profile - Travelling Straight Edge (SP/TSE); Root Mean Square Vertical Acceleration (RMSVA); and International Roughness Index (IRI). Each of the pavement profiles was analyzed using the Runway Roughness Analysis Program (R-RAP), an MS-DOS software program selected for use by Transport Canada as a part of this study. Each of the analysis methodologies selected provide a good indication of the actual runway roughness levels.

A complementary field study was completed in order to allow correlation between the roughness values measured using the Portable Universal Roughness Device (PURD), the Maysmeter and the Riding Comfort Index (RCI) procedures with the SP/TSE, RMSVA and IRI roughness values calculated using the R-RAP software. A relatively good correlation was found.

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16. Résumé

La présente recherche visait à évaluer l'état actuel de la technologie d'acquisition et d'analyse du profil en long des chaussées aéronautiques dans le but de recommander une ou plusieurs techniques à Transports Canada. Les chercheurs ont analysé des relevés profilométriques de cinq chaussées aéronautiques de Transports Canada, recueillis à l'aide d'un profilomètre numérique incrémental (Dipstick^{R}), ainsi que ceux de quatre autres chaussées. Les trois méthodes d'analyse retenues ont été : "Surface Profile - Travelling Straight Edge (SP/TSE), Root Mean Square Vertical Acceleration (RMSVA)" et celle de l'indice international d'uni (IRI). Chacun des relevés profilométriques a été analysé à l'aide d'un programme informatique (logiciel de type MS-DOS) désigné "Programme d'analyse de l'uni des chaussées aéronautiques (PAUCA)" et retenu par Transports Canada aux fins de la présente étude. L'analyse des résultats fournis par chacune de ces méthodes révèle que toutes offrent une bonne indication de la qualité de l'uni des chaussées aéronautiques auscultées.

Les chercheurs ont procédé à une étude complémentaire sur le terrain afin de vérifier la corrélation des valeurs d'uni fournies par l'appareil PURD, le profilomètre Maysmeter et la technique de l'indice de confort de roulement (RCI) avec les résultats du traitement informatique (PAUCA) des valeurs fournies par les techniques SP/TSE, RMSVA et IRI (indice international d'uni). Les chercheurs ont déterminé que la corrélation des valeurs était relativement bonne.

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Chaussée aéronautique, piste d'atterrissage, uni, profil, matériels, corrélation.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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SUMMARY

The degree, type and location of roughness in a runway pavement surface can have direct impact on the operation and safety of aircraft. The equipment used to measure pavement roughness and subsequent analysis techniques vary substantially, making interpretation and comparison of roughness levels difficult. John Emery Geotechnical Engineering Limited (JEGEL) was retained by the Transportation Development Centre of Transport Canada to review and assess currently available methods of collecting and analyzing longitudinal runway profiles in order to recommend a method(s) for Transport Canada use for Canadian airport runways.

In order to assess the state of current technology, a detailed literature review was completed. Based on this literature review and input from Transport Canada, three analysis methods selected were: Surface Profile - Travelling Straight Edge (SP/TSE); Root Mean Square Vertical Acceleration (RMSVA); and International Roughness Index (IRI).

Transport Canada provided pavement profile data from Canadian airport runway pavements. The runway pavements were selected by Transport Canada to represent a cross section of roughness conditions ranging from very poor to good. Each of the pavement profiles was analyzed using the Runway Roughness Analysis Program (R-RAP) an MS-DOS software program developed by JEGEL for use by Transport Canada as a part of this study.

Each of the analysis methodologies selected provide a good indication of the actual runway roughness levels. The SP/TSE methodology is simple to interpret, can be used with current Transport Canada rehabilitation warrants and provides specific information on localized, high amplitude events. The RMSVA and IRI methods provide a time stable and universally transferable base for the calibration of roughness measurement techniques and interpretation of runway roughness levels.

In order to allow correlation between pavement roughness measuring equipment and methods currently being used by Transport Canada, a complementary field study was completed. The complementary study compared the roughness values measured using the Portable Universal Roughness Device (PURD), the Maysmeter and the subjective Riding Comfort Index (RCI) procedures with the SP/TSE, RMSVA and IRI roughness values calculated from pavement profiles from fifteen roadway pavements exhibiting a wide range of roughness. The complementary study concluded that although good correlation existed between the various methods, the poor repeatability of response-type devices (PURD and Maysmeter) and the subjective nature of the RCI procedure introduce errors into the pavement roughness assessment.

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La condition, l'emplacement et le type des défauts d'uni d'une chaussée aéronautique peuvent avoir une influence directe sur le fonctionnement et la sécurité des avions au décollage et à l'atterrissage. Les matériels de contrôle de l'uni des chaussées et les techniques d'analyse correspondantes sont tellement nombreux et divers qu'il est difficile d'interpréter et de comparer les résultats fournis par chacun d'eux. Devant cette situation, le Centre de développement des transports a retenu les services de la société John Emery Geotechnical Engineering Limited (JEGEL), lui confiant la tâche de recenser et d'évaluer les matériels et méthodes couramment utilisés pour analyser le profil en long des chaussées aéronautiques. Ceci dans le but de pouvoir choisir la méthode la mieux adaptée aux besoins de Transports Canada et aux caractéristiques des aéroports canadiens.

Pour se donner une idée de l'état actuel de la technologie dans ce domaine, le contractant a commencé par procéder à une recherche documentaire exhaustive. Cette recherche et les données fournies par Transports Canada ont permis de sélectionner trois méthodes d'analyse à soumettre à une évaluation plus poussée : "Surface Profile - Travelling Straight Edge (SP/TSE), Root Mean Square Vertical Acceleration (RMSVA)" et celle de l'indice international d'uni (IRI).

Transports Canada a également fourni des données profilométriques concernant les pistes d'atterrissage des aéroports canadiens, choisis de manière à représenter l'ensemble des conditions de qualité d'uni allant de médiocre à bon. Le contractant a analysé chacun des jeux de données profilométriques au moyen d'un programme informatique (logiciel de type MS-DOS), désigné "Programme d'analyse de l'uni des chaussées aéronautiques (PAUCA)" qu'il a mis au point pour Transports Canada dans le cadre de la présente étude.

Toutes les méthodes d'analyse soumises à l'évaluation détaillée ci-dessus ont donné une indication juste de la qualité d'uni des chaussées aéronautiques auscultées. La méthode SP/TSE est d'interprétation simple, elle peut être adaptée au système actuel de justification des travaux de réfection appliqué par Transports Canada et elle permet une caractérisation descriptive des gros défauts d'uni localisés. Les méthodes "accélérométriques" (RMSVA) et de l'indice international d'uni (IRI) fournissent, quant à elles, une base permanente et universelle pour l'étalonnage des techniques de contrôle de l'uni et l'interprétation des résultats obtenus.

Afin de permettre la corrélation des données fournies par les différents matériels et techniques utilisés à l'heure actuelle par Transports Canada, le contractant a procédé à une étude complémentaire sur le terrain. La méthode adoptée a été de comparer les valeurs d'uni déterminées à l'aide d'un appareil PURD, d'un profilomètre Maysmeter et de la méthode subjective de l'indice de confort de roulement à celles obtenues après analyse, selon les méthodes SP/TSE, RMSVA et IRI, des données profilométriques caractérisant quinze chaussées routières couvrant une large gamme de qualités d'uni. La conclusion de cette étude complémentaire a été que, malgré la bonne corrélation entre les résultats des différentes méthodes évaluées, la faible répétabilité de ceux fournis par les appareils d'auscultation du type à réaction (PURD et Maysmeter) et le caractère subjectif de l'indice de confort de roulement sont de nature à fausser les estimations de la qualité de l'uni des chaussées auscultées.

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1. INTRODUCTION AND GENERAL METHODOLOGY

Although a number of computer-based roughness analysis procedures are available, each procedure varies somewhat in its technical approach and can therefore yield different results, making the interpretation and direct comparison of roughness difficult. John Emery Geotechnical Engineering Limited (JEGEL) was retained by the Transportation Development Centre of Transport Canada to review and assess currently available methods of analyzing longitudinal runway profiles and to evaluate roughness levels in order to recommend a method(s) for Transport Canada use for Canadian airport runways.

In order to assess the state of current technology, a detailed literature review was completed. Although some literature was found specifically relating to runway roughness, it became clear that research findings on highway pavement roughness would provide the most valuable information for this study. For example, in 1982, the need to correlate and calibrate roughness devices for highway use led to the International Road Roughness Experiment (IRRE).

Based on the literature review and input from Transport Canada, three analysis methods were defined for detailed assessment. Transport Canada provided pavement profile data from nine airport runway pavements.

A field study was completed to determine correlation equations between the pavement roughness measuring equipment and methods currently used by Transport Canada.

As part of this study, a user friendly, MS-DOS compatible computer program was developed to allow Transport Canada to perform the roughness analysis on profile data collected for any pavement. The roughness analysis software program is entitled "Runway Roughness Analysis Program, R-RAP". The software and user's manual have been provided under separate cover.

2. STATE OF CURRENT TECHNOLOGY: LITERATURE SURVEY

Roughness is defined as "a distortion of the pavement surface which contributes to an undesirable or uncomfortable ride" [1]*. A vehicle passing over a distorted or 'rough' pavement surface is excited in either a harmonic or transient manner, thus transferring a vertical acceleration to the vehicle passengers. The distortion of the pavement may be due to improper geometry of the designed or idealized surface as a result of deficiencies in the original construction as well as the action of repeated heavy aircraft load, material variations along the length of the runway and climatic forces. The degree to which roughness affects the safe operation of an aircraft and the comfort of its passengers is contingent on a number of factors, including the amplitude and frequency of the pavement distortions, vehicle suspension characteristics and the speed of the aircraft.

The characterization of pavement roughness is a very complex problem due to the differences in dynamic response of each vehicle traversing the pavement. Pavement roughness data must be reduced, through mathematical interpretation and simplifying assumptions, to a meaningful statistic(s) which relates roughness to serviceability.

A great deal of theoretical and practical research has been conducted to quantify the amount of roughness on highway pavements. In reviewing highway pavement roughness research for its significance on airside roughness evaluation, it is necessary to consider the principal differences between airport and highway pavements. Current methods for analyzing highway pavement roughness generally only consider an average level of roughness. Roughness analyses for airport pavements must also consider individual events (bumps) which have a more significant effect on safe aircraft operation and serviceability than continuous low level roughness. For instance, a slab stepping problem has been observed on Runway 06R/24L at Toronto-Lester B. Pearson International Airport that manifests itself as a series of regularly spaced, low magnitude 'bumps' in the takeoff areas. When an aircraft travels over these 'bumps', a harmonic vertical motion is imparted to the aircraft resulting in a 'rough ride'. The degree to which this roughness is felt is dependent upon the aircraft type, its suspension system, gear spacing, loading and velocity.

While it is clear that a review of research findings on highway pavement roughness is valuable for this study, consideration must also be given to the specific features of airside operations and pavements, noting the amplified problems due to aircraft dynamics, greater speeds, heavier loadings, and higher tire pressures. In summary, it is the intent of this study to develop a numerical analysis approach for Transport Canada use

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*Numbers in squared brackets designate references listed at the end of this report.

that provides a time stable and universally transferable base for the calibration and interpretation of runway roughness levels.

2.1 Developments in Pavement Roughness Measurement

The devices that have been developed to quantify pavement roughness over the past few decades can be divided into two basic categories: 1) profile measuring devices - equipment which is used to directly obtain pavement profile data; and 2) response measuring devices - equipment which measures vehicle response (generally as vertical acceleration) resulting from the movement over an uneven surface.

Profile measuring devices include rod and level surveys, the Digital Incremental Profiler (Dipstick^{R}), the Transportation Road Research Laboratory (TRRL) Beam, the California DOT Profilograph, the French Longitudinal Profile Analyzer (APL), etc. These devices are discussed in detail in various independent studies and manufacturers' technical information sheets [2 to 12].

Response-type devices generally use an accelerometer to indicate roughness and include equipment such as the General Motors Corporation Research Laboratory Profilometer (upon which current state-of-the-art systems such as K.J. Law 690 Profilometer* are based), Swedish Laser Road Surface Tester (Laser RST)*, Automatic Road Analyzer (ARAN)*, Portable Universal Roughness Device (PURD), K.J. Law Model 8300 Roughness Surveyor, Dynatest 5000 Roughness and Distress Meter (RDM), Maysmeter, Walker Roughness Device, etc. The merits of these devices are widely discussed in the technical literature [2 to 12]. The most commonly used roughness methods and equipment outlined above have been categorized according to scales of accuracy and reliability developed as a part of the International Road Roughness Experiment [13,14], as presented in Table 1.

Valid arguments can be advanced for the selective use of each of the above procedures, including cost, speed, accuracy, repeatability, etc. Surface profile data provide time stable measurements that do not generally require sophisticated proprietary equipment to collect, and the survey results can be used for regular comparisons with previous survey data to monitor roughness progression. Individual events or bumps can be discerned directly from profile data, and through change of slope and/or rate of change of slope analyses the profile can be related to vertical acceleration. The use of response (vertical acceleration) data is somewhat more restrictive in that it is very difficult to accurately back calculate the pavement surface profile from the integration of a vertical acceleration function. In addition, the magnitude of the vertical acceleration is dependent on the speed of the vehicle, its mass, suspension properties, etc. and therefore, the data is time dependent and generally not transferable, i.e. not easily comparable to previous survey results.

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*also measure profile to varying degrees.

Table 1 Common Roughness Measurement Methods

CLASS 1 - Precision Profiles (most accurate)
- Rod and Level
- Transportation Road Research Laboratory Beam
- Digital Incremental Profiler ('Dipstick')

CLASS 2 - Other Profilometric Methods
- California DOT Profilograph
- French Longitudinal Profile Analyzer

CLASS 3 - Response-Type Devices
- General Motors Corporation Research Laboratory Profilometer
- Swedish Laser Road Surface Tester
- Automatic Road Analyzer
- Portable Universal Roughness Device
- K.J. Law Model 8300 Roughness Surveyor
- Dynatest Model 5000 Roughness and Distress Meter
- Maysmeter
- Walker Roughness Device

CLASS 4 - Subjective Ratings (least accurate)
- Riding Comfort Index
- Present Serviceability Index

In addition, the acceleration measured in a passenger vehicle is not the same as that experienced in an aircraft and therefore, additional correlations must be introduced to relate the two accelerations.

To determine the actual effect of pavement roughness on aircraft operations, it would be necessary to instrument each specific aircraft of concern and measure the actual vertical accelerations experienced at different locations (pilot seat, passenger compartment, gear assemblies etc.) Reference aircraft accelerations could be developed in order to establish limiting roughness criteria for each aircraft. Unfortunately, there are a wide range of aircraft in use at Canadian facilities and each have their own unique response parameters. As such, vertical acceleration data collected for one aircraft is not generally transferable to another [15].

2.2 Developments in Roughness Characterization

As stated previously, roughness is measured in terms of vehicular reaction to deviations of the pavement from a true plane. In addition to the wide variety of equipment available to measure roughness, an equally wide variety of analysis methodologies have been considered in the technical literature for roughness characterization. Several international meetings and experiments such as the International Road Roughness

Experiment [14,15] and Ann Arbor Road Profilometer Meeting [6] were conducted in an attempt to standardize roughness data collection and analysis techniques for highway pavements. In Canada, a similar workshop entitled "State of the Art on the Use of Road Roughness Meters" [16] was convened in 1981. Although some agreement was reached at these technical meetings regarding the use of the Average Rectified Slope (ARS) and Quarter Car Index (QCI) for the World Bank International Road Roughness Experiment (IRRE) for highway pavements, it was recommended that additional studies be undertaken.

The most commonly used analysis techniques include:

a) Surface Profile and Travelling Straight Edge Analyses (SP/TSE);

b) Average Rectified Slope (ARS) as used in the calculation of the International Roughness Index (IRI);

c) Root Mean Square Vertical Acceleration (RMSVA);

d) Power Spectral Density Analyses (PSD);

e) Methods that utilize vehicle response simulations such as the Quarter Car Model (QCM), Half Car Model (HCM), Full Car Model (FCM) etc.; and

f) Subjective response indices such as Ride Comfort Index (RCI), Present Serviceability Index (PSI), etc.

There can be a wide degree of variation within each of the above analysis techniques. The major components of each methodology are discussed in the following sections. These commonly used analysis techniques for summarizing pavement roughness, and their primary advantages and disadvantages, are summarized in Table 2.

2.2.1 Surface Profile and Travelling Straight Edge Analyses

Many authors, including Darlington [2] and Carey [17], have suggested that a pavement surface profile provides the most reliable measure of pavement roughness. Basically, a profile is a detailed record of pavement surface elevations, with roughness, therefore, determined as a statistic that summarizes the amount of deviation from a 'smooth' profile. However, the amount of elevation data required to adequately determine the pavement surface profile can be quite voluminous depending on the distance between measuring stations. In order to obtain an accurate representation of a runway pavement surface, elevation data is generally collected at 300 to 600 mm intervals. This interval is considered small enough to minimize the random error caused by the selection of the starting point for the profile measurements. The 'true' value of roughness can only be calculated by defining the profile using a limiting function as the distance between the measurement points approaches zero.

Table 2 Commonly Used Analysis Techniques for Summarizing Pavement Roughness

Type of Analysis	Input Data	Advantages	Disadvantages
Pavement profile comparison over time.	Pavement surface elevations.	Method provides an actual physical representation of pavement profile and changes in the profile with time.	Unable to determine the effect of changes on aircraft response. Unable to compare results with other pavements.
Roughness Value (measure of vertical displacement of pavement per unit length).	Pavement surface elevations.	Method provides an overall summary statistic which can be compared to other pavements.	Does not account for specific high amplitude events.
Slope Variance (mean squared deviation of the pavement slope from its mean square).	Pavement surface elevations or accelerometer data.	Identifies areas where rapid changes in the profile occur.	Does not account for specific high amplitude events.
Profile Index (measure of vertical displacement of pavement per unit length in excess of a defined width 'blanking band').	Pavement surface elevations.	Filters out low amplitude events which are dampened by the aircraft suspension and are not generally felt as roughness. Specific high amplitude events can be identified.	Summary statistic does not account for specific high amplitude events.
Deviation from straight edge.	Pavement surface elevations.	Provides an excellent accounting of specific high amplitude events. Simple, physical representation.	Summary statistic does not account for specific high amplitude events.

Table 2 Commonly Used Analysis Techniques for Summarizing Pavement Roughness (continued)

Type of Analysis	Input Data	Advantages	Disadvantages
Average Rectified Slope (measure of accumulated suspension of a vehicle traversing a profile).	Pavement surface elevations or accelerometer data.	Standard used for International Roughness Index.	Does not account for specific high amplitude events. IRI utilizes theoretical vehicle response parameters which are not relevant to aircraft.
Root Mean Square vertical acceleration (root mean square difference between adjacent profile slopes).	Pavement surface elevations or acceleration data.	Provides a time stable assessment methodology. Correlatible to passenger discomfort. Roughness of various wavelengths can be identified.	Does not account for specific high amplitude events. Pavement profile anomalies of wavelengths equal to the the calculation base length are not accounted for.
Power Spectral Density	Pavement surface elevations or acceleration data.	Identifies the extent to which wavelengths in a specific band contribute to pavement roughness.	Unable to distinguish between relative levels of roughness. Analysis is complicated and time consuming.
Subjective Response Values	Pavement roughness subjectively assessed by a trained rating panel.	Inexpensive.	Poor repeatability.
Mathematical Model	Various.	Attempts to simulate actual aircraft response to pavement roughness.	Analysis is complicated and time consuming. Vehicle parameters must be assigned for each type of aircraft.

In analyzing surface profile data, the absolute elevations can be quite deceiving. Due to their length, the large majority of runway pavements follow the general topography of the adjacent land and gentle, gross variations in longitudinal runway profile do not significantly affect aircraft operation from a roughness point of view. To avoid the influence from low frequency/long wavelength components (usually classified as 'waviness' rather than 'roughness'), several authors [18,19] have suggested filtering the measured profile elevations using a Moving Average Filter. A Moving Average Filter processes the elevation at each station by calculating the algebraic difference between the elevation at that station and the average elevation over the filtering interval length. The filtering interval length is generally chosen as equal to the longest wavelength at which roughness is being measured. For typical commercial jet aircraft, this wavelength is generally between 30 and 120 metres [20,21], with wavelengths less than 60 metres contributing most to the response of aircraft.

Other authors such as Williamson [22] have suggested the use of a Recursive Filter, developed by converting the analog profile data to a digital form, then taking the tangent form of the squared-magnitude approximating function of the sixth order. The sixth order filter was suggested due to its sharp cutoff effects which adequately account for filter end effects near the beginning and end of the data record. Williamson suggests that a short interval at the beginning and end of the data should be excluded from the calculations to eliminate spurious waves that are introduced by the filter near the end points. This exclusion of data should apply to any recursive filter. In addition, it should be noted that some recursive filtering techniques introduce phase shifts that vary with frequency and distort the profile. In order to eliminate this effect, Shanks [23] has suggested that the analog profile data be filtered forward and then the digital output profile filtered backward, thereby causing the phase shifts of the two operations to cancel each other out, yielding a filtered output free of phase shift.

The type of filtering technique selected will generally be governed by the intended end use of the data. As each filtering technique produces its own distortion in the filtered results, careful consideration must be given to the type of filter used for any pavement profile analysis and care must be taken to ensure that the objective of relating the pavement profile to the vehicle using it is not lost in computational complexity. If the pavement profile data is reviewed at a sufficiently detailed vertical scale, the use of a filter for the data is considered unnecessary.

The Roughness Value (RV), as described by Nakamura and Michael [24], is simply a measure of vertical displacement in millimetres per kilometre of travel. This value indicates the total overall vertical displacement per unit length but does not however, identify specific roughness events.

Research conducted by Sonnenburg [25] on airport runway roughness criteria has suggested that a band width equal to the standard deviation of the vertical displacement be used to indicate general roughness levels, with the standard deviations of the changes in elevation and the rate of change in elevation considered for detailed indices.

The Present Serviceability Index (PSI), a subjective index developed as part of the AASHO Road Test [26], uses Slope Variance (SV) and empirical equations to determine the roughness of a section [27]. The slope variance is the mean squared deviation of the slope from its mean square.

As some component of the pavement roughness is undoubtedly dampened by the vehicle's suspension, an index such as Roughness Value can give misleading results. For example, a pavement exhibiting a great deal of short wavelength roughness which is effectively dampened by a vehicle's suspension system could have a Roughness Value of similar magnitude to that of a pavement exhibiting localized more pronounced 'bumps'. However, the difference of each profile on aircraft operations could be severe, noting that continuous short wavelength roughness may not generally affect the operation of the aircraft while several locally large bumps would have adverse effects.

In order to account for the dampening effect of the vehicle's suspension system, roughness analyses from devices such as the California Profilograph, Rainhart Profilograph and Maysmeter are generally reported as a Profile Index (PI) [28,29]. This Profile Index is a measure of vertical displacement in millimetres per kilometre in excess of a 5 mm 'blanking band'. The width of this blanking band has been selected for highway pavements to account for general deficiencies due to construction or general distress.

One of the most basic techniques for characterizing pavement roughness is to measure pavement surface deviations from a travelling straight edge. A travelling straight edge is simulated in the analysis stage by connecting two points on a profile with a straight line and measuring the maximum deviation of the profile from this line. The length of the straight edge can be varied in order to account for roughness of various wavelengths. The maximum calculated deviations from the straight edge can then be compared to maximum allowable deviations specified to assess pavement roughness. This is the analysis procedure currently specified by Transport Canada [30,31] using a 4.6 metre straight edge length.

The travelling straight edge method provides an excellent indication of the severity of individual events or bumps in a profile. However, the method does not account for roughness of wavelengths greater than the length of the span. A summary statistic for this analysis method can be determined by calculating the measure of vertical displacement of pavement per unit length, in a manner similar to the Roughness Value (RV) statistic.

2.2.2 Average Rectified Slope (ARS)

The rectified slope of a profile is simply a measure of the accumulated displacement of the suspension of a vehicle traversing a given profile. The Average Rectified Slope (ARS) value provides an overall measure for the pavement. The International Roughness Index (IRI) [13,14,32] was developed in order to standardize suspension systems for

various vehicles used in measuring roughness. Rather than using a mechanical system upon which Response Type Road Roughness Measuring Systems (RTRRMS) are based, the IRI is based on a mathematical model. The computational procedure for the model is called a Quarter-Car Simulation (QCS), with the mathematical model representing a RTRRMS having a single wheel. As the amount of vehicle suspension will vary with speed, a standard speed of 80 kph is specified for all surveys. The IRI model computes four variables as functions of the measured profile and uses a Taylor Series Expansion to simulate the reference vehicle.

If the IRI were to be converted for use on aircraft pavements, an appropriate aircraft model would have to be developed. The non-linear response of aircraft suspension systems and varying weight of an aircraft on a pavement (dependent on the amount of uplift on its wings) would make the use of a representative set of aircraft parameters very difficult. In addition, the IRI is an averaged statistic and therefore does not identify specific events such as bumps or depressions. However, the IRI provides a standardized statistic and can be used to compare relative roughness on an international basis.

2.2.3 Root Mean Square Vertical Acceleration (RMSVA)

Several analysis techniques have been developed based on the rate of change of slope or vertical acceleration of a vehicle. Studies have shown that passenger discomfort is directly related to the amount of time a human can endure various levels of whole body acceleration [33,34]. Therefore, a roughness statistic based on whole body acceleration would appear to be the most appropriate in assessing comfort levels.

While instantaneous values of acceleration may not be particularly important (unless they take on a harmonic motion which excites the normal harmonic frequency of the aircraft), the peak value of acceleration may be more significant from a damage point-of-view. Several authors, including Spangler [35], have recommended a maximum allowable peak acceleration value of 0.4 times the gravitational acceleration as a limiting roughness criteria. The Mean Absolute Vertical Acceleration (MAVA) statistic summarizes the overall acceleration response of the profile.

The peak value of acceleration is a time dependent quantity. In order to obtain a time stable assessment methodology incorporating acceleration, it is necessary to calculate the Root Mean Square Vertical Acceleration (RMSVA) statistic [36]. The RMSVA can be defined as the root mean square difference between adjacent profiles slopes, where each slope is the ratio of elevation change to the corresponding horizontal distance interval selected. An advantage to this type of analysis is its ease of calculation for different base lengths. The RMSVA can be computed for any base length that is a multiple of the measurement interval. Unfortunately, for pavement profile anomalies of wavelengths equal to the base length, this analysis does not provide a response, i.e. the RMSVA is equal to 0. This lack of response for wavelengths equal to the base length is not generally

a problem since it has been determined that the majority of pavement roughness can be characterized by two or three base lengths.

Correlations completed as a part of the International Road Roughness Experiment revealed an excellent correlation between the Quarter-Car Index (QCI) and the RMSVA at the 1.0 and 2.5 metre base lengths. Since the RMSVA statistic is easier to compute than the QCI, the RMSVA was adopted to redefine the QCI in the Experiment [14,37].

2.2.4 Power Spectral Density (PSD) Analyses

A Power Spectral Density (PSD) analysis assumes that a vehicle moving over an uneven pavement surface will experience random motion. The overall motion can be considered to be composed of a continuous spectrum of frequencies whose individual amplitudes vary in a random manner. The PSD shows the extent to which wavelengths in a specific band width contribute to the pavement roughness. A PSD estimate for each band width is determined by summing the squared amplitude of the magnitude of the random event over the length of the section. The sum of the squared amplitudes is then divided by the length of the section and then by the band width for each section to obtain an average value for the band width. This process is repeated for all of the bands within the filtering interval since random motion contains a continuous distribution of frequencies. The PSD can then be plotted against wavelength, with the area under the curve equal to the mean square variance of the roughness profile. PSD analyses to define both highway and runway roughness have been used by several authors [38 to 44].

Although it appears that PSD analysis is capable of adequately defining pavement roughness, studies such as those reported by Coleman [45] and Holbrook [46] have suggested that the PSD function may not provide an adequate criterion for determining pavement maintenance needs. The PSD function is unable to distinguish between relative levels of roughness. The PSD function merely represents a general impression of the roughness associated with the various wavelengths over the pavement roughness profile. Therefore, it is unable to discern between several localized high amplitude distortions and a larger number of low amplitude distortions. The ability to differentiate between high and low amplitude distortions is of paramount importance from a runway evaluation and maintenance perspective.

2.2.5 Subjective Response Values

Prior to the development of roughness measuring devices, pavement roughness was subjectively assessed by one or more trained raters. The Canadian Good Roads Association (now Roads and Transportation Association of Canada) developed the Riding Comfort Index (RCI) scale [47]. A standard procedure was adopted using a panel of raters to evaluate the riding quality of a pavement on a scale from 1 to 10. This procedure is also currently specified for use by Transport Canada (AK-68-33-199 [30]).

Given the variable and subjective nature of rating panels, the accuracy and repeatability of this type of approach is questionable. However, if the panel is comprised of personnel knowledgeable in pavement serviceability concepts, it can provide a practical, inexpensive method of comparative roughness assessment and does not require a complicated analysis technique.

2.2.6 Mathematical Model Simulations

Several methods of analyzing the effects of pavement roughness have been developed by relating the pavement profile to the acceleration response of an 'ideal' vehicle. The IRI, using the Quarter-Car Index discussed previously, is one such model. Other more sophisticated models include the Half-Car Model (HCM) and the Full-Car Model (FCM). Noting that the 'ideal' vehicle is a conventional passenger car travelling at a speed of about 80 kph, none of these models are particularly relevant for airport pavements for more than a relative comparison of roughness between sections. In order to simulate aircraft dynamic response to runway roughness, Gerardi [13] has developed a mathematical model (TAXI) that includes rigid-body degrees of freedom of pitch, roll and vertical and horizontal translation and up to 30 flexible modes of vibration. The necessary landing gear data for typical aircraft were collected and several simulations were conducted using the 0.4 g criterion as a limiting vertical acceleration to locate rough areas of the runway.

Although quite complex in terms of its analysis technique, this type of model, if standardized to a design aircraft, may give a realistic response of an aircraft to pavement unevenness.

2.3 Recommendations for Analysis Methodology

In order to maintain a time stable and transferable base for the calibration and interpretation of runway roughness levels, it is extremely important that the analysis methodology utilize the pavement longitudinal profile taken from accurate elevation measurements as an input parameter. Airport runways are usually designed to very strict roughness standards and therefore, a small error in the profile measurement could lead to very large errors when roughness statistics are calculated from the measured profiles. The runway profile should be measured using at least an IRRE Class 1 device such as a rod and level, Transportation Road Research (TRRL) Beam or Digital Incremental Profiler (Dipstick^{R}).

Based on the literature review findings and subsequent input from Transport Canada, three roughness analysis methods were selected for use. The three analysis methods selected were: Surface Profile/Travelling Straight Edge (SP/TSE); Root Mean Square Vertical Acceleration (RMSVA); and International Roughness Index (IRI). The SP/TSE method was selected as it is simple to interpret, provides a good indication of specific high amplitude events and can be used with the current Transport Canada

rehabilitation warrants. The RMSVA method should provide a roughness value equable to that experienced by aircraft crew and passengers. The IRI method was chosen to allow relative comparisons of airport pavement roughness using a variety of roughness measurement techniques or devices on an international scale.

3. TECHNICAL DESCRIPTION OF SELECTED ROUGHNESS ANALYSIS METHODOLOGIES

A description of the theories behind the SP/TSE, RMSVA and IRI analysis methodologies is given in the following sections. It has been assumed that the statistics are calculated from longitudinal profile data. The longitudinal profile is a vertical section along the pavement that gives the elevation of the surface as a function of longitudinal distance along the runway.

In order to accurately represent the profile, elevation measurements are generally collected at spacings of 300 mm to 600 mm. The selection of the starting point of the profile measurement will introduce a random error into the calculations. Profile data collected at discreet intervals only provide an estimate of the 'true' profile. As the length of the measuring interval is usually fixed, care should be taken to ensure that the measured profile is much greater in length than the measuring interval. Significant error could be introduced for relatively short sections.

3.1 Surface Profile/Travelling Straight Edge

The Surface Profile/Travelling straight Edge (SP/TSE) analysis methodology is one of the simplest methods of measuring profile roughness. The straight edge is basically a simply supported beam with a surface contact sensor located at mid-length as shown in Figure 1. The length of the straight edge can be varied but is generally kept between 1 to about 60 metres in length. The straight edge is 'moved' along the profile and the deviation of the profile at the midpoint of the straight edge is calculated. Mathematically, the deviation is defined as:

$$d_{(i)} = Y_{(i)} - [Y_{(i+k)} + Y_{(i-k)}]/2 \qquad (1)$$

where: Y = elevation at point (mm)
d = profile deviation (mm)

The SP/TSE Summary statistic is defined as:

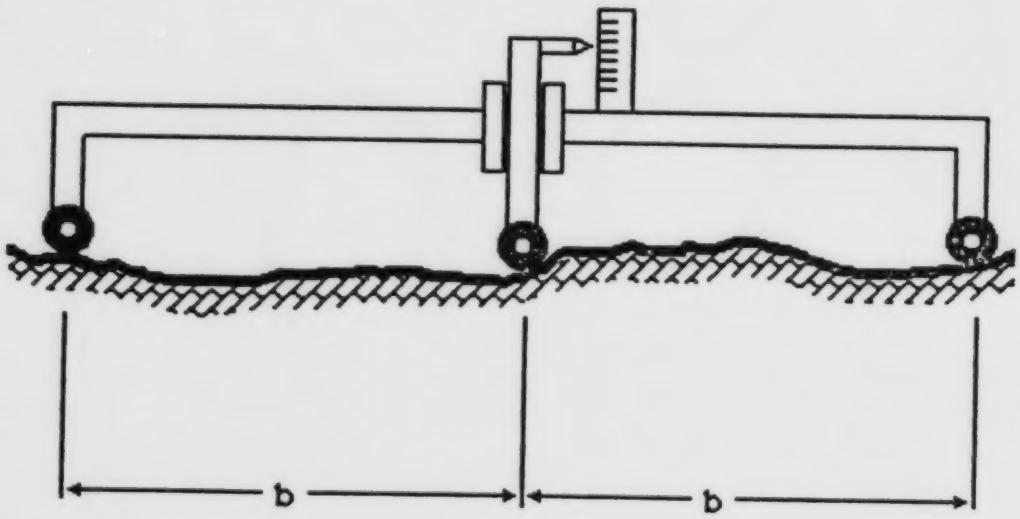
$$SP/TSE = \sum_{i=1}^{n} \frac{|\, d_{(i)} \,|}{ndx} \qquad (2)$$

where: n = number of elevation points
dx = distance between profile measurements
$|\, d_{(i)} \,|$ = absolute value of $d_{(i)}$

Several summary statistics can be obtained in analyzing the SP/TSE data. The simplest statistic is the sum of the absolute deviations from the straight edge per unit length. The maximum deviation for a particular

FIGURE 1

Taken from World Bank Technical Paper #45, "The International Road Roughness Experiment" [13]



Schematic Representation of a Mechanical Rolling Straightedge

runway will depend on the physical characteristics of the runway and straight edge length. The dynamic response of various aircraft to the pavement profile deviations will largely depend on the individual aircraft characteristics including the distance between the landing gear, landing gear suspension parameters, natural frequency of the aircraft suspension and the speed at which it traverses the profile.

As discussed previously, the length of straight edge used for the analysis is variable. The 'critical' straight edge length generally used by most North American agencies is between 3 and 4.5 metres in length. In this study, a 3.0 metre straight edge length was selected to allow comparison of the results with airport pavements criteria as defined by Transport Canada and the U.S. Army Corps of Engineers. In addition, SP/TSE calculations were also completed for straight edge lengths of 10 and 30 metres. These straight edge lengths were selected to represent the shortest and longest gear spacings of aircraft typically using Canadian airfields.

The primary advantage of a straight edge based analysis technique is that it is one of the simplest methods of measurement and is easily visualized for interpretation. This method has been used by Transport Canada in the past and will therefore probably be acceptable for use at the regional centres for general assessment of the runways.

3.2 Root Mean Square Vertical Acceleration

The Root Mean Square Vertical Acceleration (RMSVA) is defined as the root mean square difference between adjacent profile slopes, where each slope is the ratio of elevation change to the corresponding horizontal distance interval selected. The vertical acceleration (VA) portion of this statistic is not really a true 'acceleration', as acceleration indicates a response to an event. This vertical acceleration is actually calculated as the second derivative of the elevation. The VA portion of the RMSVA can be visually interpreted as being equivalent to the mid-chord deviation that would be obtained measuring from a rolling straight edge at a particular base length and multiplied by a scale factor.

Mathematically, VA is defined as:

$$VA_{(i)} = [y_{(i+k)} + y_{(i-k)} - 2y_{(i)}]\, b^{-2} \qquad (3)$$

where:
- y = elevation at point (mm)
- i = index, corresponding to the i^{th} profile elevation measure
- b = base length (m)
- k = b/dx
- dx = distance between profile measurements

RMSVA can be calculated using the following expression:

$$RMSVA_b = [1/(n-2k) \sum_{i=k+1}^{n=k} VA_{(i)}{}^2]^{1/2} \quad (4)$$

where: n = number of measurements

Correlations completed as a part of the International Road Roughness Experiment indicated an excellent correlation between the Quarter-Car Index (QCI) and the RMSVA at the 1.0 and 2.5 metre lengths. Since the QCI is used to standardize response type road roughness measuring systems, the RMSVA at a particular, or combination of, base length(s) may provide a reliable indication of aircraft response to pavement roughness.

A primary disadvantage of the RMSVA analysis, as previously discussed, is that this analysis does not provide a response for pavement profiles having wavelengths equal to the base length, i.e. the RMSVA is equal to 0.

3.3 International Roughness Index

The International Roughness Index (IRI) was developed during the International Road Roughness Experiment (IRRE) conducted by the World Bank, Brazil in 1982. The IRI is defined as the average rectified slope of a profile being traversed by a particular reference vehicle at a speed of 80 kph. The rectified slope of a profile is simply the measure of the accumulated suspension response of the vehicle traversing the profile.

The calculation of the IRI is accomplished by computing four variables as functions of the measured profile. These four variables model the response of a reference vehicle traversing the profile. The variables are initialized for the IRI calculation by taking the average slope of the first 11 metres of the profile. Mathematically, the IRI is calculated as follows:

Variable initialization:

$$Z_1' = Z_3' = (Y_n - Y_1)/11 \quad (5)$$

$$Z_2' = Z_4' = 0 \quad (6)$$

$$n = (11/d_x) + 1 \quad (7)$$

where: Y_n = the n^{th} profile elevation point
Y_1 = the first profile elevation point
dx = the sample interval

The response variables are calculated as:

$$Z_1 = (S_{11} * Z_{1,}') + (S_{12} * Z_{2,}') + (S_{13} * Z_{3,}') + (S_{14} * Z_{4,}') + (P_1 * Y_{,}') \quad (8)$$
$$Z_2 = (S_{21} * Z_{1,}') + (S_{22} * Z_{2,}') + (S_{23} * Z_{3,}') + (S_{24} * Z_{4,}') + (P_2 * Y_{,}') \quad (9)$$
$$Z_3 = (S_{31} * Z_{1,}') + (S_{32} * Z_{2,}') + (S_{33} * Z_{3,}') + (S_{34} * Z_{4,}') + (P_3 * Y_{,}') \quad (10)$$
$$Z_4 = (S_{41} * Z_1') + (S_{42} * Z_2') + (S_{43} * Z_3') + (S_{44} * Z_4') + (P_4 * Y') \quad (11)$$

where: $Y_{,}' = (Y_i - Y_{i-1})/dx$ (12)
Z_j' = Z_j from previous position for j = 1 to 4
S_{ij} = coefficient fixed for specific measuring interval
P_j = coefficient fixed for specific measuring interval

The S_{ij} and P_j coefficients are calculated using a Taylor Series expansion. A list of the coefficients calculated for various measuring intervals, along with a basic program developed as a part of the IRRE to calculate the coefficients for any measuring interval, is provided in the Runway Roughness Analysis Program (R-RAP) User's Manual. Once the response variables are calculated for each position, the rectified slope (RS) of the profile is calculated for each point by the following equation:

$$RS_i = Z_3 - Z_1 \quad (13)$$

The IRI statistic is simply the average rectified slope over the total length of the measured section:

$$IRI = \frac{1}{(n-1)} \sum_{i=2}^{n} RS_i \quad (14)$$

As IRI is a response-governed statistic, i.e. a function of the vehicle response to the profile and not simply a function of the profile, it is necessary to calculate IRI in both directions along the profile. This is particularly important for runways, noting that aircraft may use the runway in both directions depending on the wind direction.

The IRI statistic is desirable for the characterization of roughness as it provides a measure of the roughness actually experienced by an 'ideal' vehicle traversing a profile. The main disadvantage of IRI, as it is currently defined, is that the 'ideal' vehicle is an automobile. To get a true response for aircraft pavements, an appropriate aircraft model would have to be developed. The non-linear response of aircraft suspension systems (even within specific aircraft types) and varying loads induced by aircraft on pavements (dependent on the amount of uplift on its wings) makes the development of a set of aircraft response parameters very difficult.

4. FIELD CORRELATION STUDY

In order to compare the SP/TSE, RMSVA and IRI runway roughness analysis statistics derived using profile elevation data with roughness measurement equipment and roughness statistics currently used by Transport Canada, a complementary field correlation study was completed in October/November of 1988. A total of fifteen pavement sections in the Ottawa area were identified by Transport Canada for roughness testing. These pavement sections, each 320 metres in length, were selected by Transport Canada to represent a wide range of surface roughness conditions, and had been previously tested by Transport Canada.

Transport Canada provided Portable Universal Roughness Device (PURD) and Maysmeter roughness data for each of two units and Riding Comfort Index (RCI) panel ratings for each of the sections. Pavement profile data was obtained by JEGEL at 300 mm intervals using a Digital Incremental Profiler (Dipstick^{R}) following the manufacturer's operating procedures. As the PURD and Maysmeter measure the response of a vehicle to a profile, elevation data was collected in both wheelpaths for one lane in each section. The SP/TSE, RMSVA and IRI statistics were calculated for each wheelpath using the R-RAP program. The statistics for each wheelpath were averaged to determine a single value for use in the correlation analysis. It should be noted that the roughness did not vary significantly between the inner and outer wheelpath. However, the inner (driver's side) wheelpath generally exhibited a lower level of roughness than the outer (passenger's side) wheelpath. This increased roughness in the outer wheelpath is attributed to the pavement edge effects and roadway/shoulder interaction.

The RMSVA summary statistic was calculated for a range of base lengths. As discussed previously, it is desirable to use a relatively short base length to more closely approximate the 'true' response. As described in Section 2.2.3, correlations completed as part of the International Road Roughness Experiment (IRRE) revealed excellent correlation between the Quarter Car Index and RMSVA at the 1.0 and 2.5 metre base lengths. As the measuring interval used at the IRRE was different than that used by the Dipstick^{R}, it was decided to use a base length of 1.2 metres for this correlation. Similarly, a preliminary analysis with several straight edge lengths, suggested that the most appropriate straight edge length for correlation purposes was 3.0 metres. The roughness statistics for each section are summarized in Table 3. Correlation/calibration equations for each analysis procedure were derived using the method of least squares linear regression technique. As the data from the PURD and Maysmeter units appeared to be curvilinear, a logarithmic relationship was used for the correlation of these devices. The roughness correlation equations and correlation coefficients are summarized in Table 4. The correlation data and least squares regression curves are presented in Appendix A.

Table 3 Roughness Equipment/Statistic Correlation Data

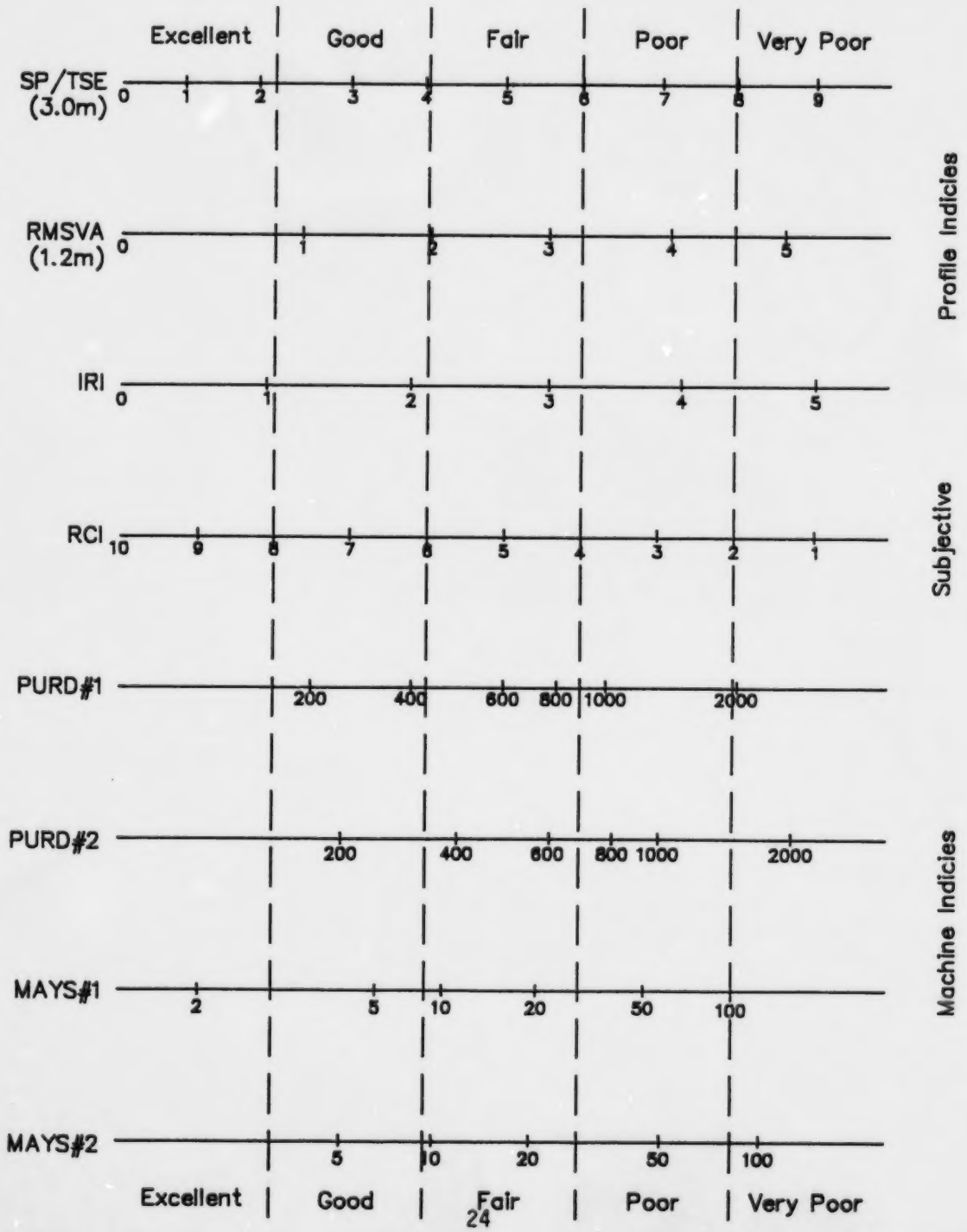
Section	RMSVA Base Length			IRI Direction		SP/TSE Straight Edge Length			RCI	PURD	PURD	MAYS	MAYS
	1.2 m	1.8 m	3.0 m	--->	<---	3.0 m	10.1 m	30.5 m		#1	#2	#1	#2
T1	3.05	1.74	0.96	3.28	3.15	5.95	18.01	79.77	5.3	604.00	516.50	20.30	19.70
T2	2.57	1.37	0.65	2.41	2.40	4.58	12.06	50.01	5.5	551.50	435.00	14.40	15.10
T3	1.53	0.88	0.53	1.58	1.60	3.11	11.41	80.31	7.4	264.00	205.00	3.20	5.10
T4	1.48	0.87	0.48	1.65	1.64	3.21	9.42	49.53	7.1	247.00	201.50	4.10	4.40
T5	1.41	0.96	0.65	1.81	1.80	3.30	14.51	90.50	6.6	262.00	225.50	4.40	6.30
T6	0.95	0.57	0.33	1.07	1.06	2.10	7.26	41.79	7.9	190.50	185.50	2.80	3.20
T7	3.74	1.90	0.68	3.17	3.16	6.28	9.97	30.73	3.7	886.00	729.00	38.80	35.60
T8	3.58	1.88	0.93	3.45	3.51	6.66	15.54	56.32	3.6	861.00	647.50	26.60	24.50
T9	0.85	0.57	0.41	1.01	0.99	1.97	9.84	69.39	7.4	215.50	174.00	3.90	4.80
T10	1.08	0.70	0.48	1.32	1.30	2.21	9.13	37.81	6.5	253.00	219.50	5.40	6.80
T11	2.27	1.20	0.59	2.42	2.40	4.39	11.96	39.24	4.6	521.00	431.00	19.10	19.60
T12	3.63	1.86	0.88	3.44	3.46	6.14	15.39	58.05	4.1	806.50	653.00	31.60	30.40
T13	2.99	1.70	1.00	3.39	3.28	5.90	20.86	106.91	4.5	566.50	496.00	25.40	27.30
T14	2.68	1.36	0.60	2.77	2.76	5.37	10.02	34.98	4.9	1035.50	791.50	14.90	14.70
T15	1.75	1.03	0.60	1.98	1.97	3.69	12.21	47.57	5.8	339.50	272.00	10.30	9.90

The RMSVA and IRI statistics correlated well with each other, and with the Maysmeter equipment, as given by high correlation coefficients ranging from 0.89 to 0.95. The correlation coefficients for RSMVA and IRI to RCI reduce to 0.85 and 0.87 respectively. Correlation coefficients of 0.84 and 0.89 were proven for RMSVA and IRI to respective PURD units. The lower correlation with the PURD units was anticipated due to the variability of the PURD roughness data. A low correlation coefficient with the RCI was also expected due to the subjective nature of the RCI procedure. The SP/TSE correlation with RCI, Maysmeter and PURD equipment ranged from 0.76 to 0.85. Based on the correlation analysis, it appears that RMSVA for a base length of 1.2 metres correlates the most directly with the RCI, PURD and Maysmeter roughness values. A Roughness Measures Correlation Chart was developed for graphical comparison of the roughness indices used for this report. The correlation chart is given as Figure 2.

Table 4 Roughness Statistic Correlation Equations

Dependent Variable	Independent Variable	Independent Variable Coefficient	Constant	Correlation Coefficient
RMSVA	IRI	1.104111	-0.320640	0.95
	SP/TSE	0.630717	-0.562020	0.92
	RCI	-0.662550	5.985077	0.87
	LOG (PURD #1)	3.770944	-7.714440	0.88
	LOG (PURD #2)	3.981213	-7.936440	0.89
	LOG (MAYS #1)	2.404843	-0.231270	0.90
	LOG (MAYS #2)	2.767950	-0.709640	0.89
IRI	SP/TSE	0.553484	-0.139850	0.91
	RCI	-0.578400	5.588446	0.85
	LOG (PURD #1)	3.249614	-6.259270	0.84
	LOG (PURD #2)	3.449671	-6.498760	0.86
	LOG (MAYS #1)	2.103099	0.157847	0.88
	LOG (MAYS #2)	2.432158	-0.272750	0.89
SP/TSE	RCI	-0.937840	9.742894	0.76
	LOG (PURD #1)	5.461523	-9.975270	0.80
	LOG (PURD #2)	5.877269	-10.580900	0.84
	LOG (MAYS #1)	3.422040	0.925215	0.79
	LOG (MAYS #2)	3.881344	0.305545	0.76
RCI	LOG (PURD #1)	-5.258160	19.533380	0.87
	LOG (PURD #2)	-5.538990	19.811360	0.87
	LOG (MAYS #1)	-3.490540	9.239705	0.95
	LOG (MAYS #2)	-4.011260	9.927332	0.95
PURD #1	LOG (MAYS #1)	605.498700	-114.065000	0.73
	LOG (MAYS #2)	686.890600	-223.840000	0.71
PURD #2	LOG (MAYS #1)	480.916300	-81.033900	0.78
	LOG (MAYS #2)	546.701600	-169.435000	0.76

Figure 2
Roughness Measures Correlation Chart



5. ANALYSIS OF AIRPORT PAVEMENT LONGITUDINAL PROFILE DATA

Transport Canada (Airports Authority Group) supplied longitudinal profile data for nine airport runways for this project. The profile data for the first five runways (C-1 to C-5) was collected at 0.305 metre (1 foot) intervals using a Digital Incremental Profiler (Dipstick^R). Details on the Dipstick^R and its use were documented in a Transport Canada Airports Authority Group publication, "Assessment of the Dipstick for Measurement of Runway Profiles", dated January 1988 [48]. The profile data for the last four runways (S-1 to S-4) was collected at 0.5 metre intervals. A general description of the runways selected is given in Table 5. The runways were selected by Transport Canada to encompass a cross section of roughness conditions ranging from very poor to good.

Table 5
Runway Longitudinal Profile Data

Runway	Runway Length (m)	Measured Length (m)	Date	Measuring Interval (m)	# Elev. Readings	RCI
C-1	2438	2133	1986	0.305	7000	6 1/2 - 7
C-2	3658	2743	1986	0.305	9000	5 1/2 - 6
C-3	766	732	1986	0.305	2403	6 1/2 - 7
C-4	2957	1828	1986	0.305	6000	6 - 6 1/2
C-5	2134	1525	1986	0.305	5005	4 - 5
S-1	650	650	1988	0.500	1300	N/A
S-2	703	703	1988	0.500	1407	N/A
S-3	705	705	1988	0.500	1411	N/A
S-4	707	707	1988	0.500	1414	N/A

The elevation profiles for each runway are given in Figures 3 through 11. The elevation profiles are each scaled to the maximum and minimum elevations found in the profile data set. As such, scale factors make it very difficult to develop any direct comparisons of the relative roughness levels between the runways using only the elevation profile data. Although the profile in Figure 9 appears more rough than the profile in Figure 11, the vertical scale in Figure 11 is almost ten times that of Figure 9.

FIGURE 3

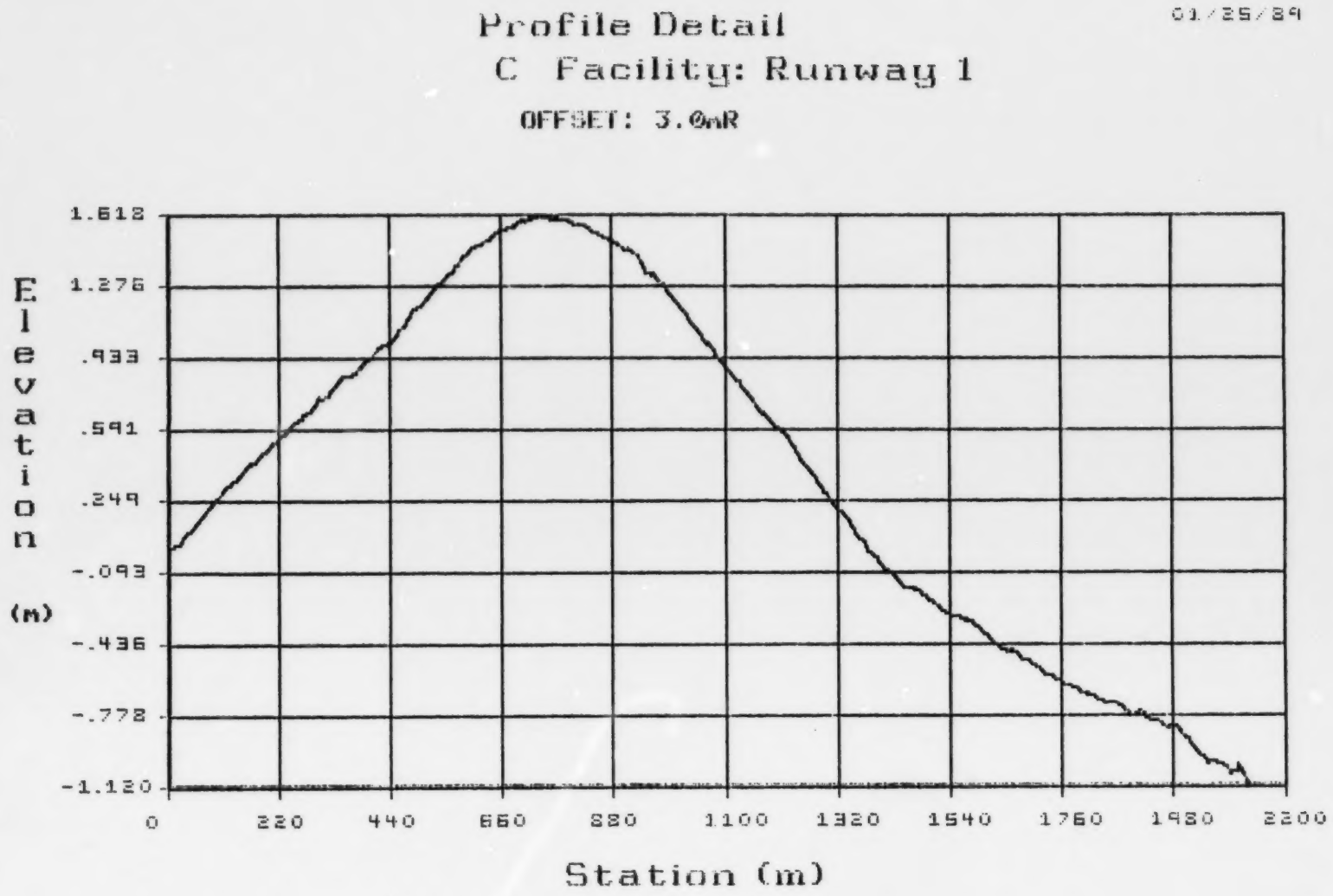

Profile Detail
01/25/89
C Facility: Runway 1
OFFSET: 3.0mR
Elevation (m)
1.612
1.276
.933
.591
.249
-.093
-.436
-.778
-1.120
0
220
440
660
880
1100
1320
1540
1760
1980
2200
Station (m)

FIGURE 4

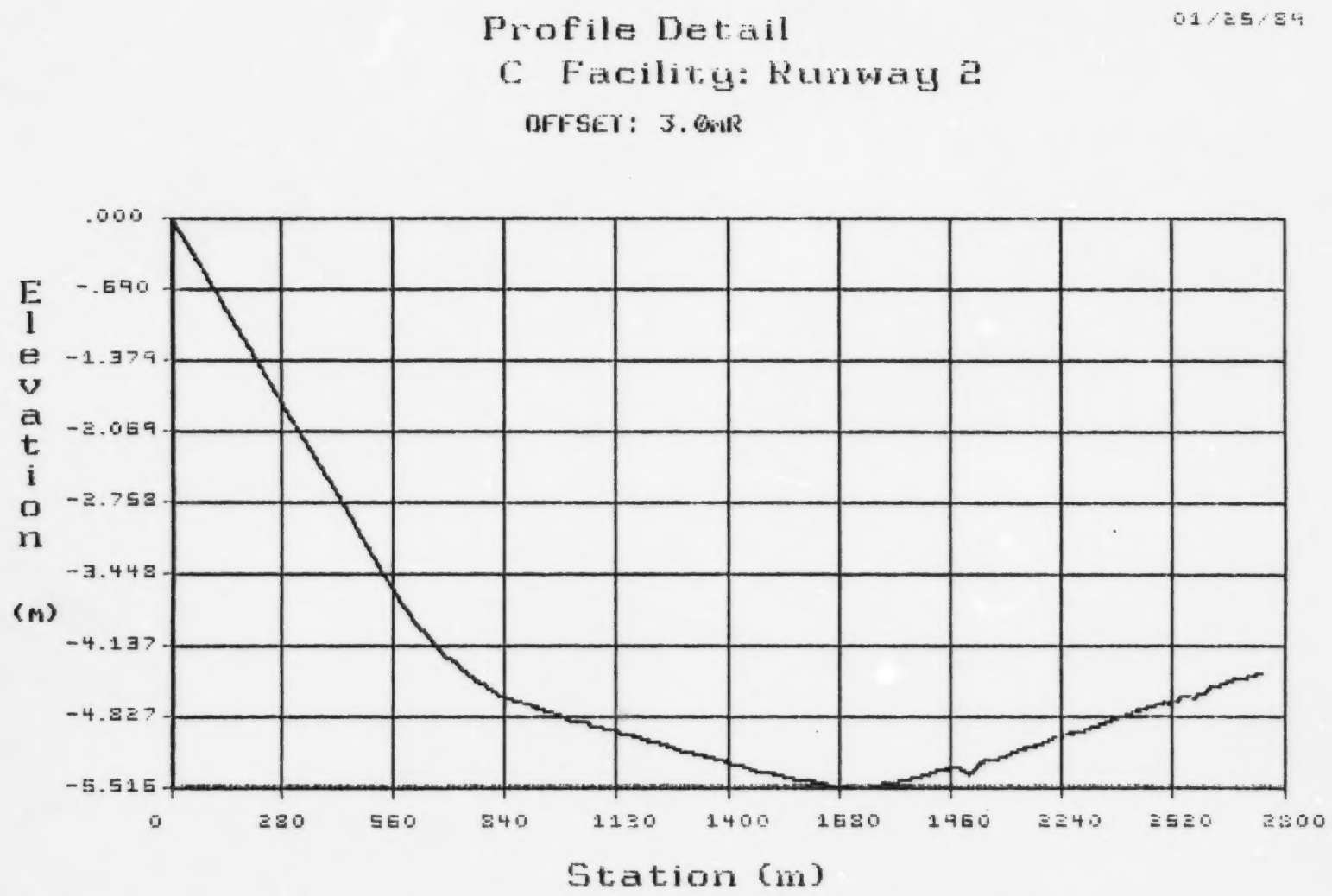

Profile Detail
01/25/84
C Facility: Runway 2
OFFSET: 3.0mR
.000
-.690
-1.379
-2.069
-2.758
-3.448
-4.137
-4.827
-5.516
Elevation (m)
0
280
560
840
1120
1400
1680
1960
2240
2520
2800
Station (m)

FIGURE 5

Profile Detail

C Facility: Runway 3

01/25/89

OFFSET: 3.0%R

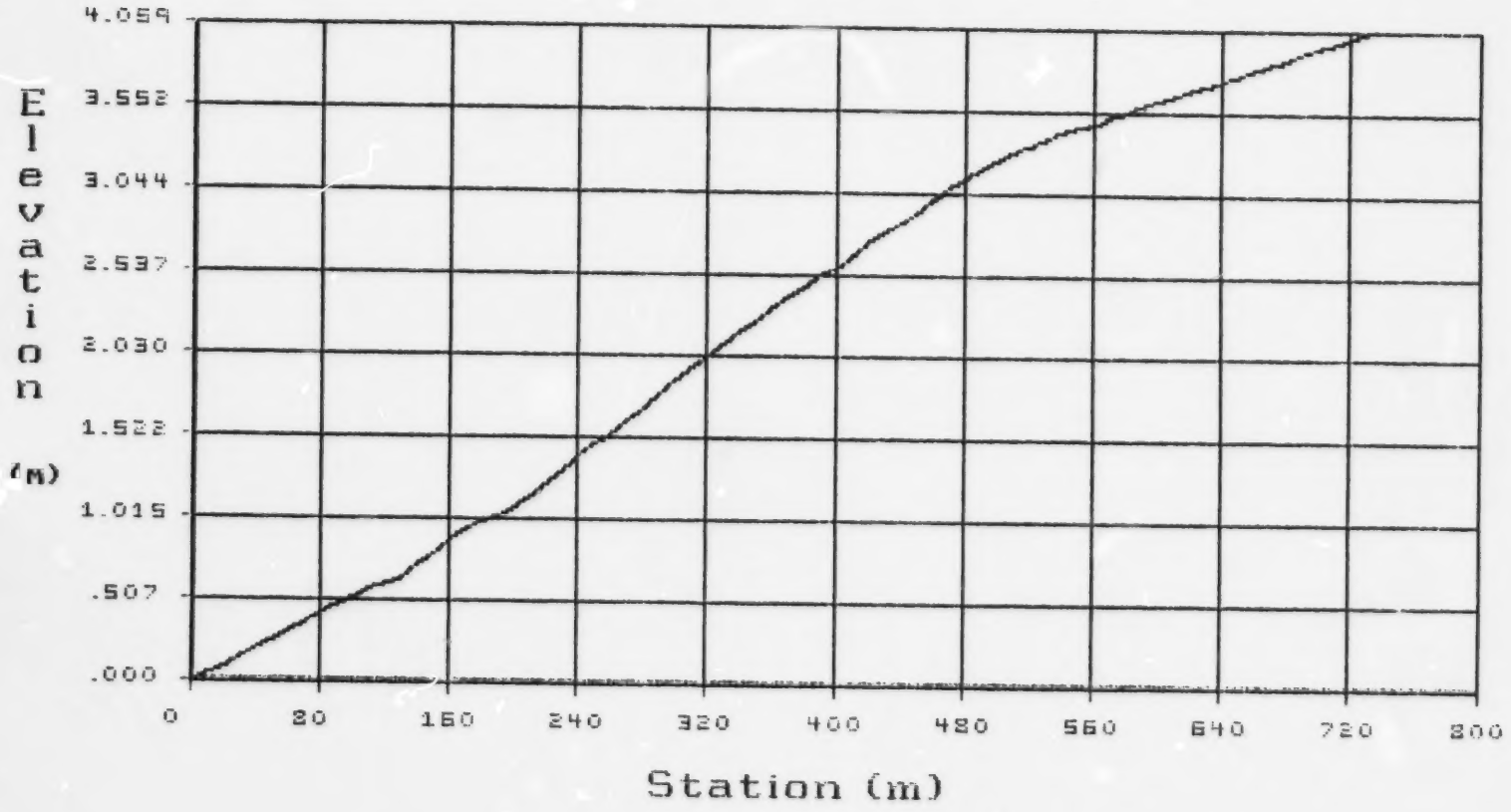


FIGURE 6

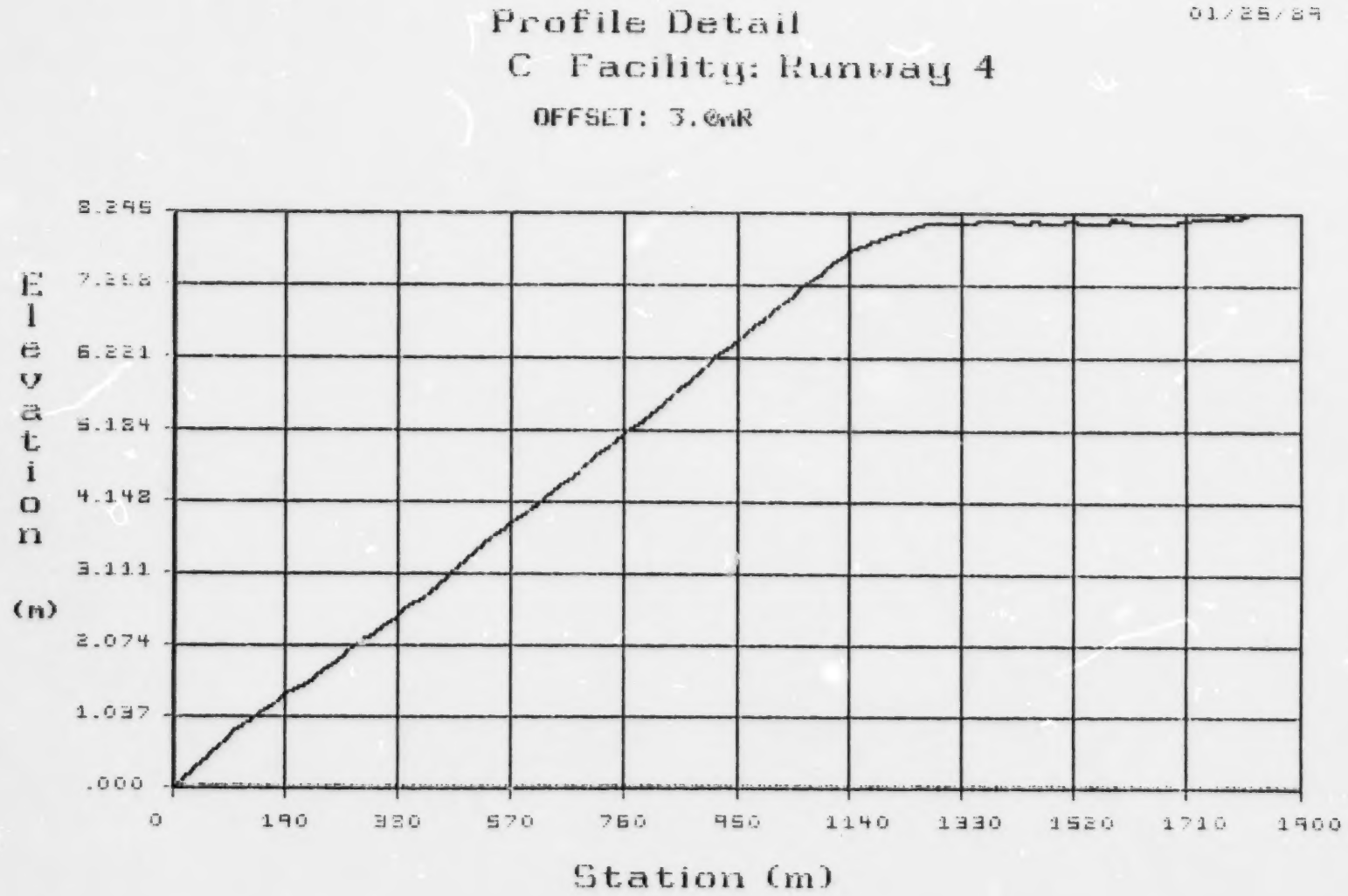

Profile Detail
01/25/89
C Facility: Runway 4
OFFSET: 3.0mR
Elevation (m)
8.295
7.258
6.221
5.184
4.148
3.111
2.074
1.037
.000
0
190
380
570
760
950
1140
1330
1520
1710
1900
Station (m)

FIGURE 7

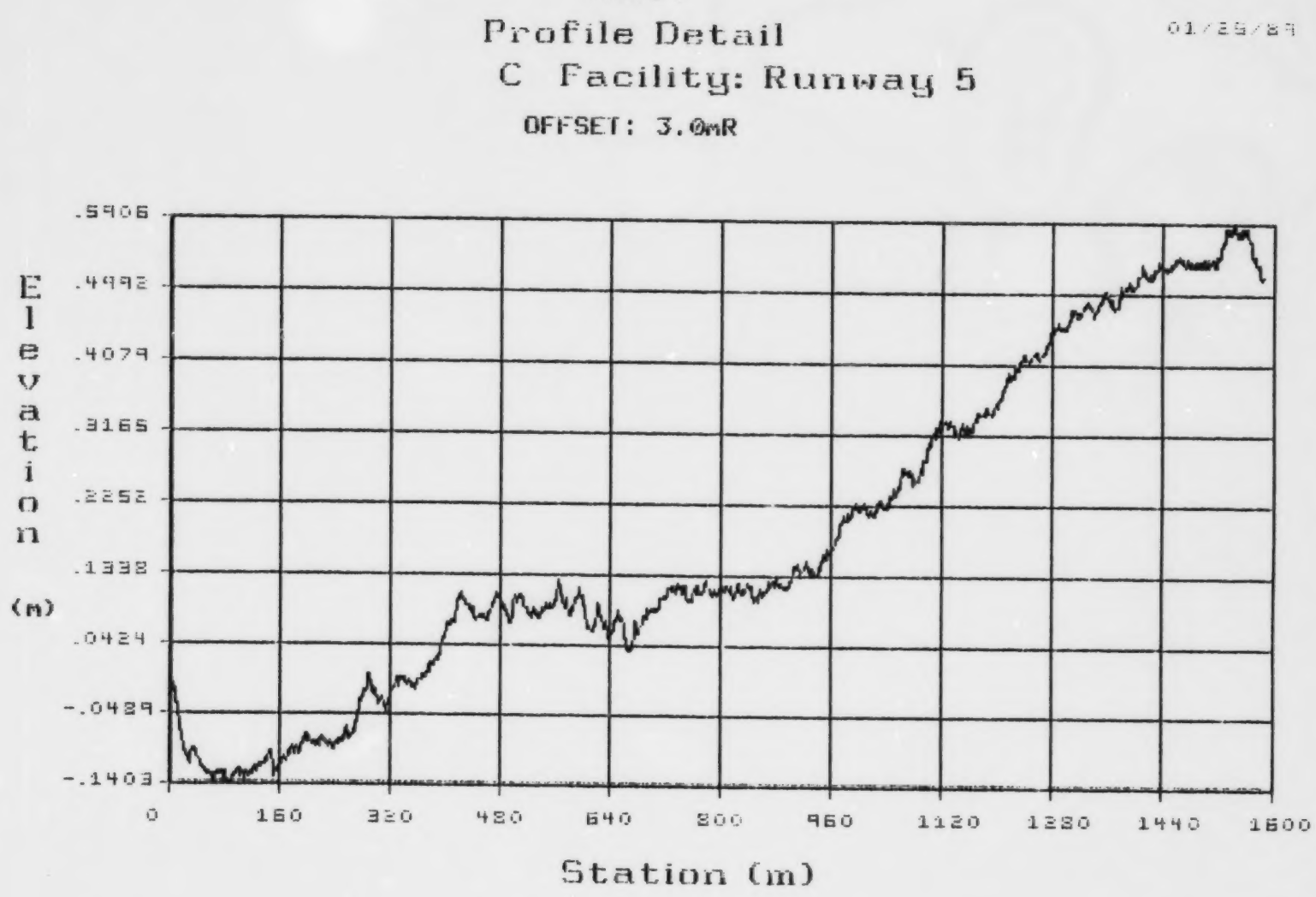

Profile Detail
01/25/89
C Facility: Runway 5
OFFSET: 3.0mR
Elevation (m)
.5906
.4992
.4079
.3165
.2252
.1338
.0424
-.0489
-.1403
0
160
320
480
640
800
960
1120
1280
1440
1600
Station (m)

FIGURE 8

Profile Detail

02/14/84

S Facility: Runway 1

OFFSET: 0.0m

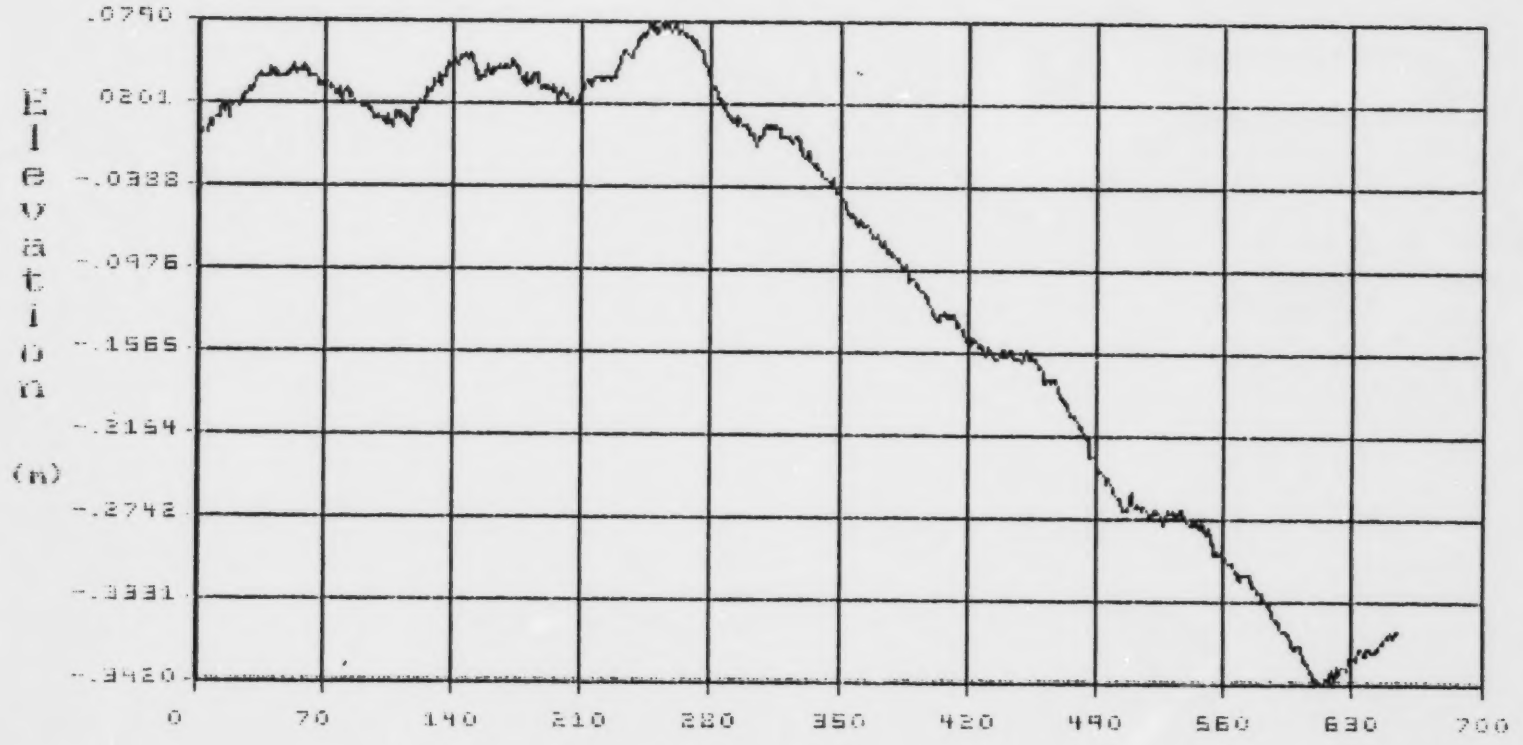


FIGURE 9

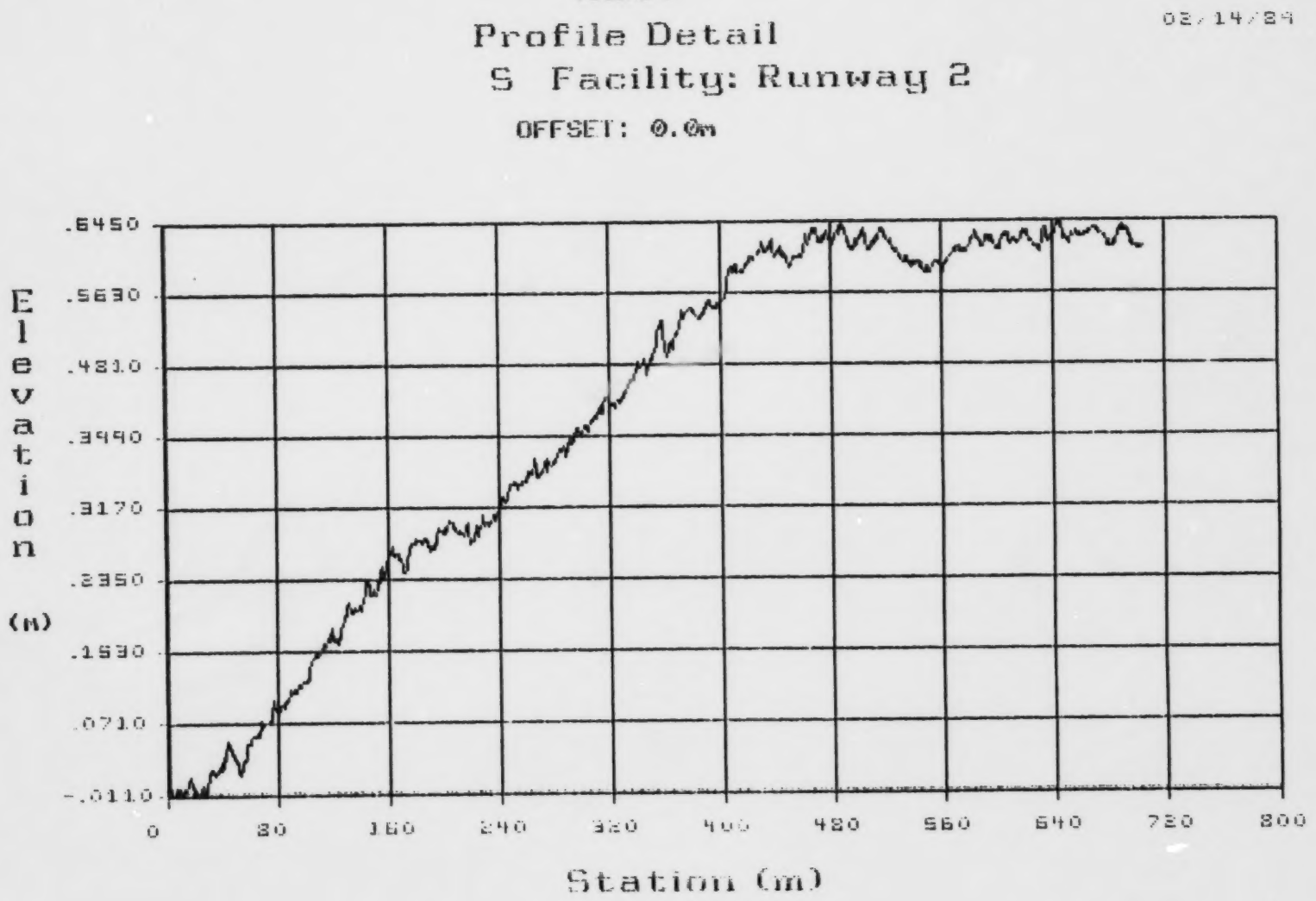

Profile Detail
S Facility: Runway 2
OFFSET: 0.0m
02/14/89
Elevation (m)
.6450
.5630
.4810
.3990
.3170
.2350
.1530
.0710
-.0110
0
80
160
240
320
400
480
560
640
720
800
Station (m)

FIGURE 10

Profile Detail

02/15/84

S Facility: Runway 3

OFFSET: 0.0m

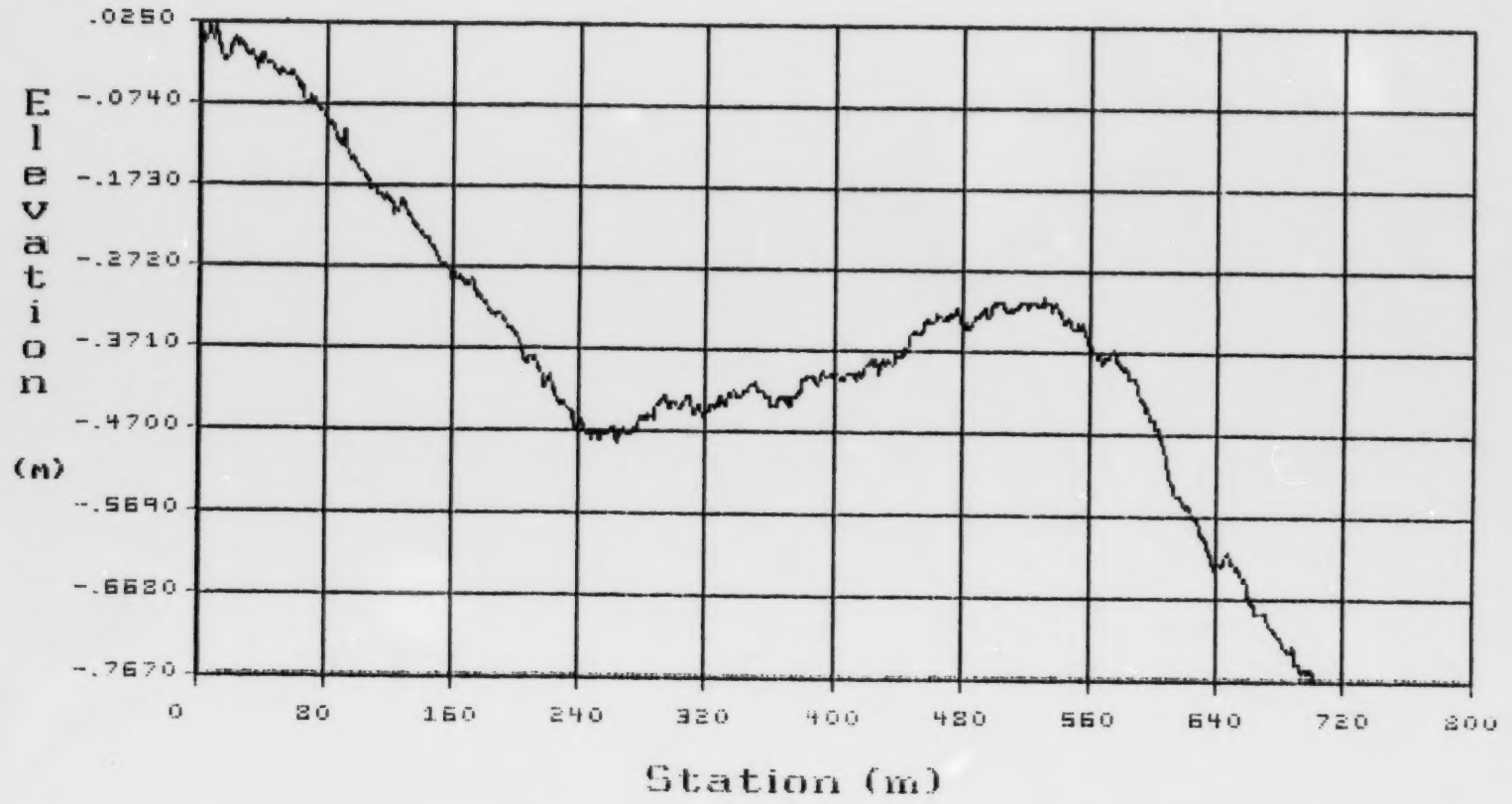


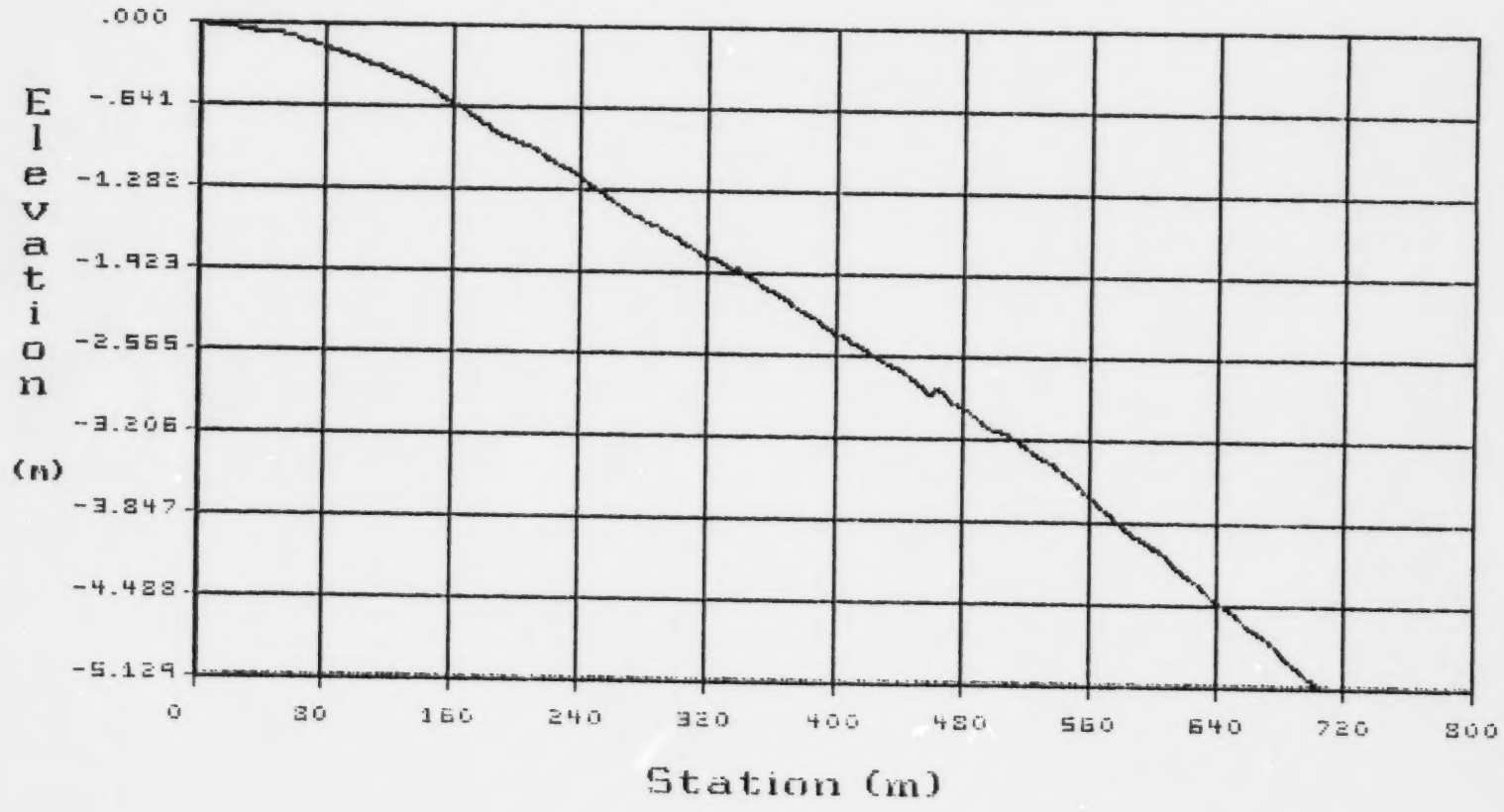
FIGURE 11

Profile Detail

02/15/84

S Facility: Runway 4

OFFSET: 0.0m



The SP/TSE, RMSVA and IRI summary statistics were calculated for each of the runways using the Runway Roughness Analysis Program (R-RAP) developed for this project. A general flow chart for the R-RAP program is given in Figure 12.

The results of the analysis for the five runways where elevation data was collected at 0.305 metre intervals are given in Table 6. The results of the analysis for the four runways where elevation data was collected at 0.5 metre intervals are given in Table 7. Although the IRI values can be directly compared, the RMSVA and SP/TSE roughness indices are only comparable for the same base length or straight edge length. For this project, comparisons between the data were made using a 3.0 metre base length and 3.0 metre straight edge length as these are multiples of the measuring interval for both cases. Alternatively, the RMSVA for any base length can be interpreted from a plot of RMSVA versus base length. The RMSVA was calculated for each profile for a range of base lengths. It was found that an almost linear relationship existed when the RMSVA versus base length was plotted on a log-log scale. Plots of RMSVA versus base length have been prepared for each of the runways and are given in Appendix B. A similar relationship relating the SP/TSE statistic to straight edge length was not found.

In general, each of the analyses corroborate the general perceived roughness as determined by the RCI rating panel. The analysis results and significance are discussed in more detail in the following sections.

5.1 RMSVA Analyses

The RMSVA analysis provides a good range of values enabling easy comparison of the relative roughness levels of the runways. Higher RMSVA values indicate higher levels of roughness. An RMSVA base length of 3.0 metres was selected to allow comparison of all of the runway roughness levels. At this base length, the RMSVA was found to vary from 0.44 mm/m^2 at Runway C-3 to 1.39 mm/m^2 at Runway S-2. It is interesting to note that although Runway C-1 and Runway C-3 were given similar RCI values (6 1/2 - 7) by a Transport Canada rating panel, the more rigourous RMSVA analysis indicates that Runway C-1 has a higher level of roughness than Runway C-3.

Given the current Transport Canada rehabilitation warrants for runways subjected to jet aircraft, it is suggested that runway rehabilitation could be identified by a 'terminal' RMSVA value of 1.2 mm/m^2 for the 3.0 metre base length. Using this criteria, Runways C-1, C-2, C-3, C-4, C-5 and S-1 would be considered acceptable from a roughness point of view. Runways S-3 and S-4 would be considered marginal and Runway S-2 would be unacceptable.

FIGURE 12

Runway Roughness Analysis Program (R-RAP) Flow Chart

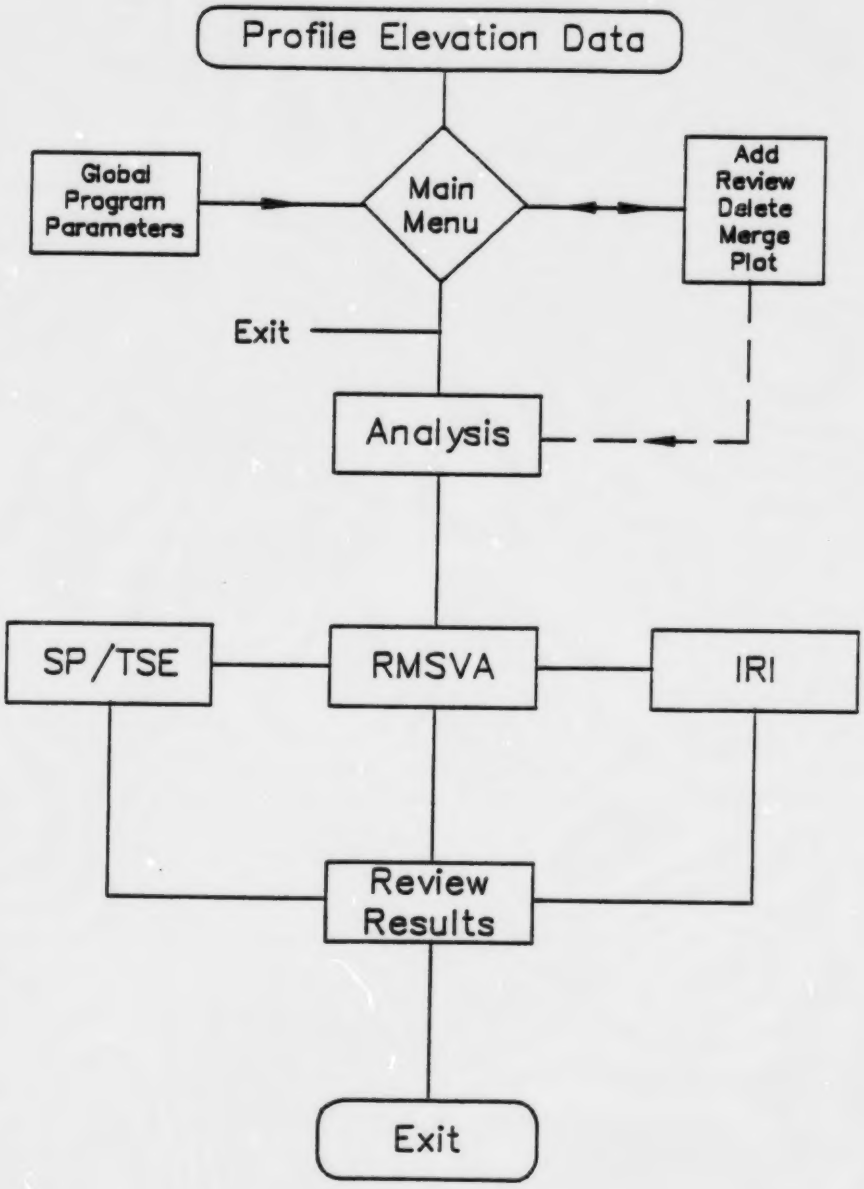


Table 6 Summary of Profile Analyses

Runways C-1 to C-5

Facility	Root Mean Square Vertical Acceleration (mm/m^2) Base Length 1.2 m	1.8 m	3.0 m	International Roughness Index (mm/m) Direction --->	<---	SP/TSE Profile Deviation Per Unit Length (mm/m) Straight Edge Length 3.0 m	10.1 m	30.5 m
RUNWAY C-1 RCI: 6 1/2-7	1.49	0.96	0.53	1.69	1.69	3.27	8.72	23.22
RUNWAY C-2 RCI: 5 1/2-6	1.62	0.96	0.49	1.78	1.77	3.56	7.52	17.54
RUNWAY C-3 RCI: 6 1/2-7	1.14	0.70	0.44	1.42	1.46	2.50	9.09	24.73
RUNWAY C-4 RCI: 6-6 1/2	1.67	0.93	0.49	1.83	1.81	3.43	8.65	29.79
RUNWAY C-5 RCI: 4-5	3.10	1.91	0.97	3.31	3.31	7.01	13.54	32.56

Table 7 Summary of Profile Analyses

Runways S-1 to S-4

Facility	Root Mean Square Vertical Acceleration (mm/m^2) Base Length 1.0 m	1.5 m	3.0 m	International Roughness Index (mm/m) Direction --->	<---	SP/TSE Profile Deviation Per Unit Length (mm/m) Straight Edge Length 3.0 m	10.0 m	30.0 m
RUNWAY S-1	4.02	1.34	0.69	3.06	3.10	3.71	6.24	12.37
RUNWAY S-2	6.27	2.36	1.39	5.17	5.16	6.08	14.63	16.98
RUNWAY S-3	6.09	2.26	1.23	4.62	4.60	5.96	11.36	18.05
RUNWAY S-4	6.46	2.22	1.22	5.09	5.00	5.85	12.22	22.63

5.2 IRI Analyses

The IRI is calculated for the profile in both ascending and descending directions as the IRI represents the directional response to a profile and aircraft can use a runway in either direction. The calculated IRI values for the five runways where elevation data was collected at 0.305 metre intervals ranged from 1.42 mm/m for Runway C-3 to 3.31 mm/m for Runway C-5. The calculated IRI values for the four runways where elevation data was measured at 0.5 metre intervals ranged from 3.06 mm/m for Runway S-1 to 5.17 mm/m for Runway S-2. The relative condition of the runways in terms of IRI is similar to that determined using the RCI ratings.

Although the International Road Roughness Experiment (IRRE) was designed with roadways as its primary focus, typical IRI values for roadway and airport pavements were also defined. An IRI value of 0 mm/m indicates absolute smoothness (no roughness). An IRI value in the order of 15 mm/m is representative of a rough, unpaved roadway. Airport runways used by jet aircraft and superhighways generally exhibit IRI values less than 2 mm/m. Typical IRI values defined in the IRRE are given in Figure 13.

It should be noted that the profile data for Runways S-1 to S-4 was measured to an elevation accuracy of ± 1 mm. This accuracy is significantly less than that used for Runways C-1 to C-5 where elevation was measured to an accuracy of ± 0.1 mm. The accuracy requirement for Class 1 precision surveys defined during the IRRE is ± 0.5 mm. Measurements to an accuracy of only ± 1 mm can yield up to 5 percent bias in the calculated IRI.

The current Transport Canada rehabilitation warrants appear to be less restrictive than those suggested by the IRRE. A maximum allowable IRI of 3.25 mm/m is suggested for Canadian airport runways. Using this criteria, Runways C-1, C-2, C-3, C-4 and S-1 would be considered acceptable from a roughness point of view. Runway C-5 would be considered marginal and Runways S-2, S-3 and S-4 would be unacceptable.

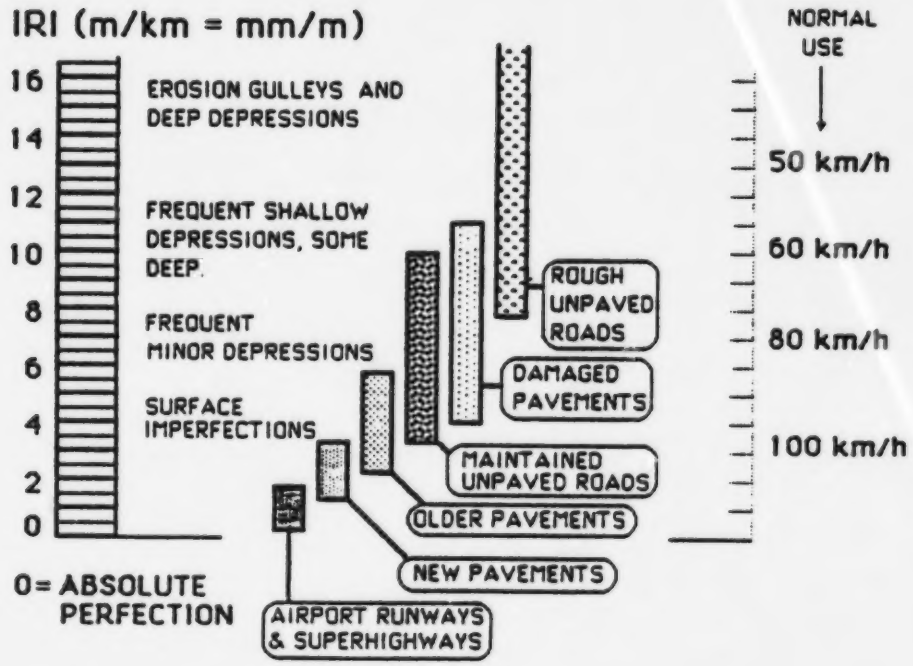
5.3 SP/TSE Analyses

The SP/TSE statistic has been calculated for straight edge lengths of 3.0, 10.1 and 30.5 metres for Runways C-1 to C-5 and 3.0, 10.0 and 30.0 metres for Runways S-1 to S-4. Similar to the RMSVA and IRI analyses, the relative roughness of the runways determined by SP/TSE analysis compare with those determined using the RCI method. The SP/TSE deviations per unit length ranged from 2.50 mm/m for Runway C-3 to 7.01 mm/m for Runway C-5 when using a 3.0 metre straight edge length. A maximum allowable deviation per unit length of 6 mm/m is recommended for use.

The profiles were generally acceptable in terms of the straight edge deviation criteria for specific high amptitude events defined in AK-68-33-199 [30], except for localized areas of Runway C-5, S-3 and S-4. AK-68-33-199 defines the critical deviation (above which corrective action should be

FIGURE 13 The IRI roughness scale.

Taken from World Bank Technical Paper #46, "Guidelines for Conducting and Calibrating Road Roughness Measurements [14]



taken) as equal to 0.9 times the square root of the straight edge length (SEL) where the SEL is measured in metres and the critical deviation is measured in centimetres.

In order to visually compare the SP/TSE results, the R-RAP program was used to generate profile deviation plots for a 3.0 metre SEL for selected sections of the 'best' and 'worst' runways. Figures 14 and 15 show the true elevation plot and profile deviation plot using the 3.0 metre SEL for selected sections of Runways C-3 and S-1. In accordance with the criteria given in AK-68-33-199, the maximum allowable deviation from a 3.0 metre SEL is 0.016 metres. Figures 14 and 15 clearly demonstrate that this maximum allowable deviation criterion is not exceeded in these sections of the profile. Figures 16, 17 and 18 give true elevation and profile deviations from the 3.0 metre SEL for selected sections of Runways C-5, S-3 and S-4 respectively. The horizontal dashed lines in these figures represent the maximum allowable deviation as defined in AK-63-33-199. Several localized areas of these profiles exhibit deviations greater than the maximum allowable deviation identifying specific areas where corrective action should be considered.

The critical deviation criteria defined in AK-63-33-199 appear to be sufficiently responsive to identify areas of high amplitude profile deviation. As such, it is recommended that this criteria continue to be used at the present time. Once a complete data base of roughness values for Canadian airports is collected, the applicability of this criteria should be reviewed with the intent of possibly reducing the allowable maximum deviation.

FIGURE 14

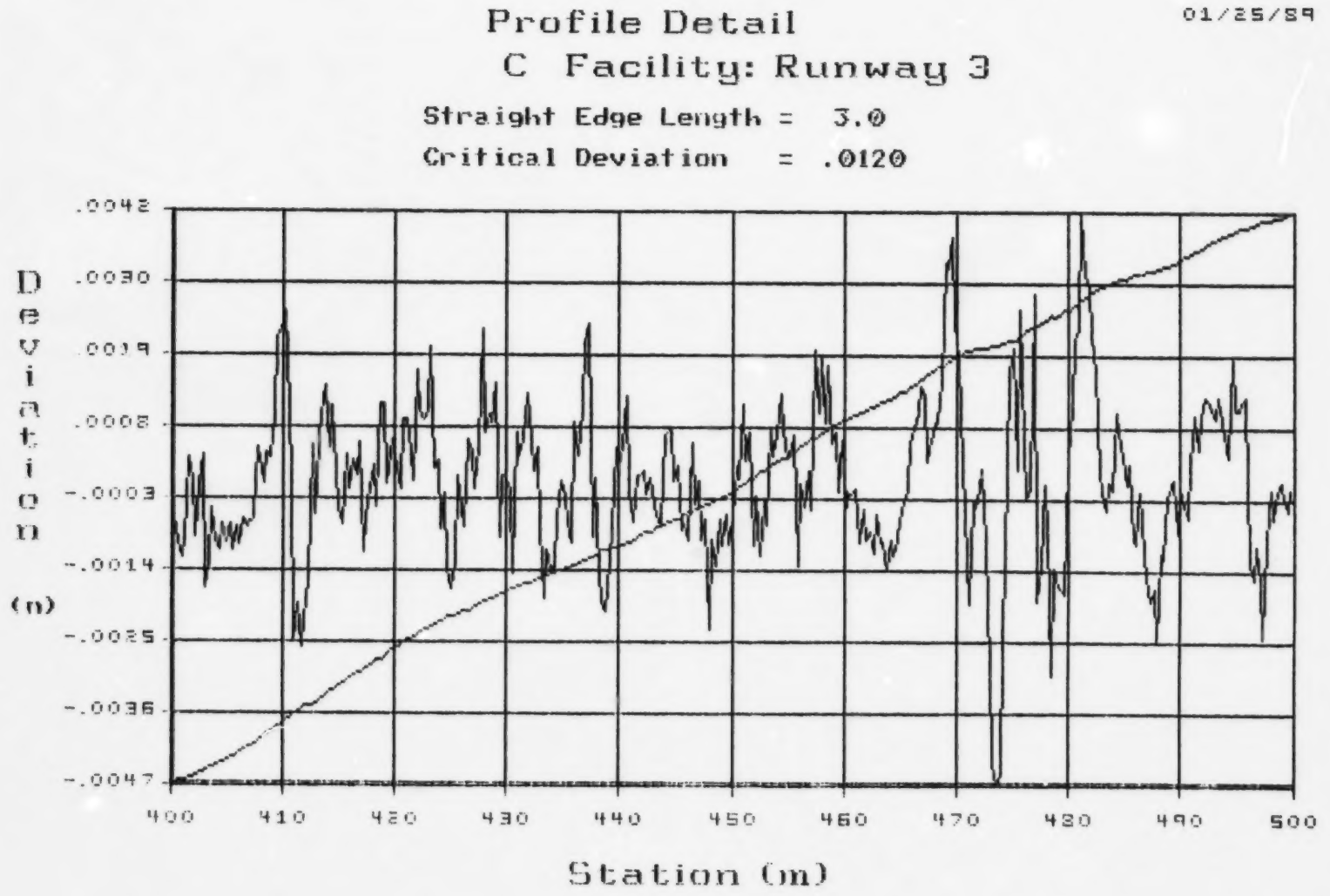

Profile Detail
01/25/89
C Facility: Runway 3
Straight Edge Length = 3.0
Critical Deviation = .0120
Deviation (n)
.0042
.0030
.0019
.0008
-.0003
-.0014
-.0025
-.0036
-.0047
400
410
420
430
440
450
460
470
480
490
500
Station (m)

FIGURE 15

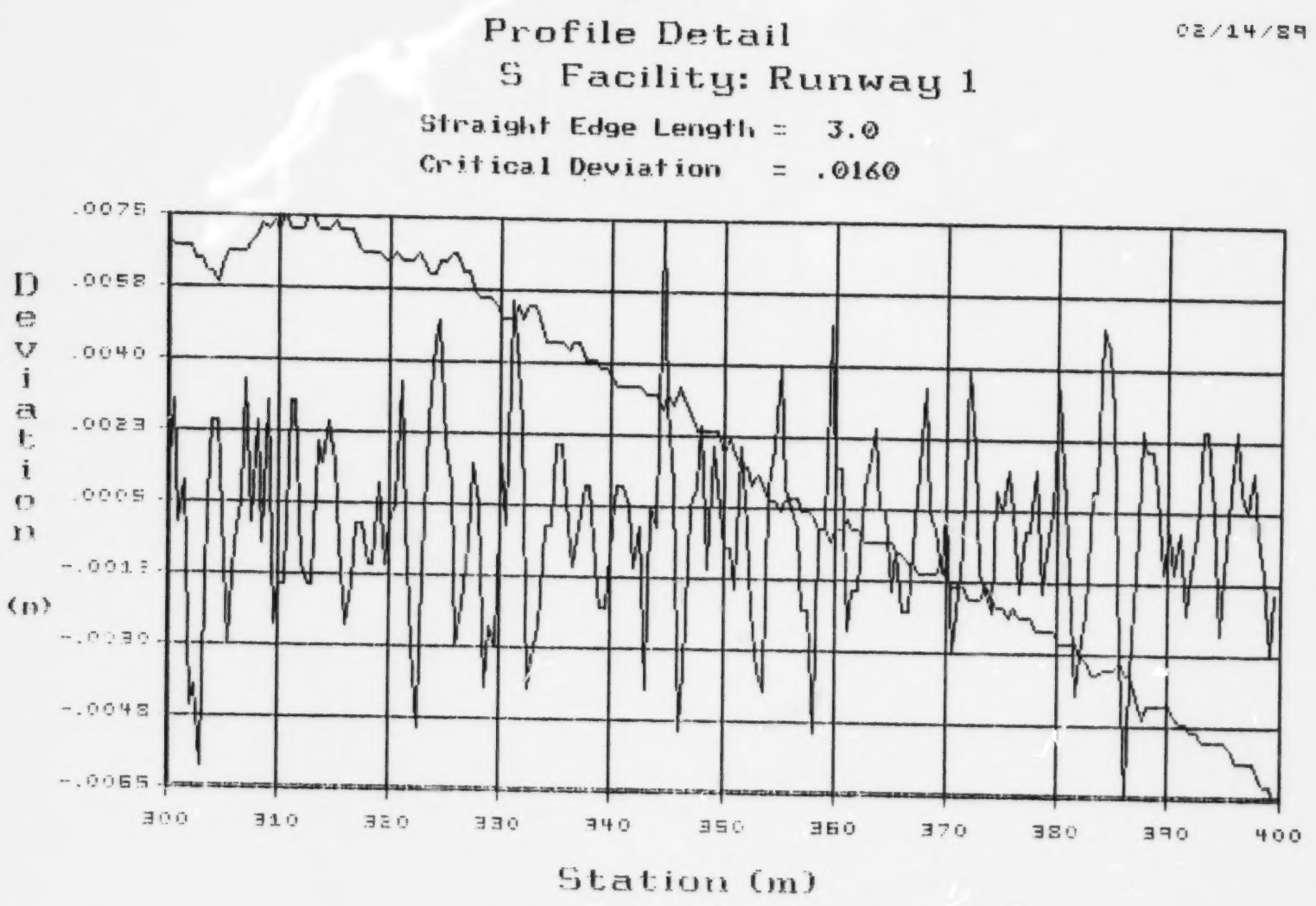

Profile Detail
02/14/89
S Facility: Runway 1
Straight Edge Length = 3.0
Critical Deviation = .0160
Deviation (in)
.0075
.0058
.0040
.0023
.0005
-.0013
-.0030
-.0048
-.0065
300
310
320
330
340
350
360
370
380
390
400
Station (m)

FIGURE 16

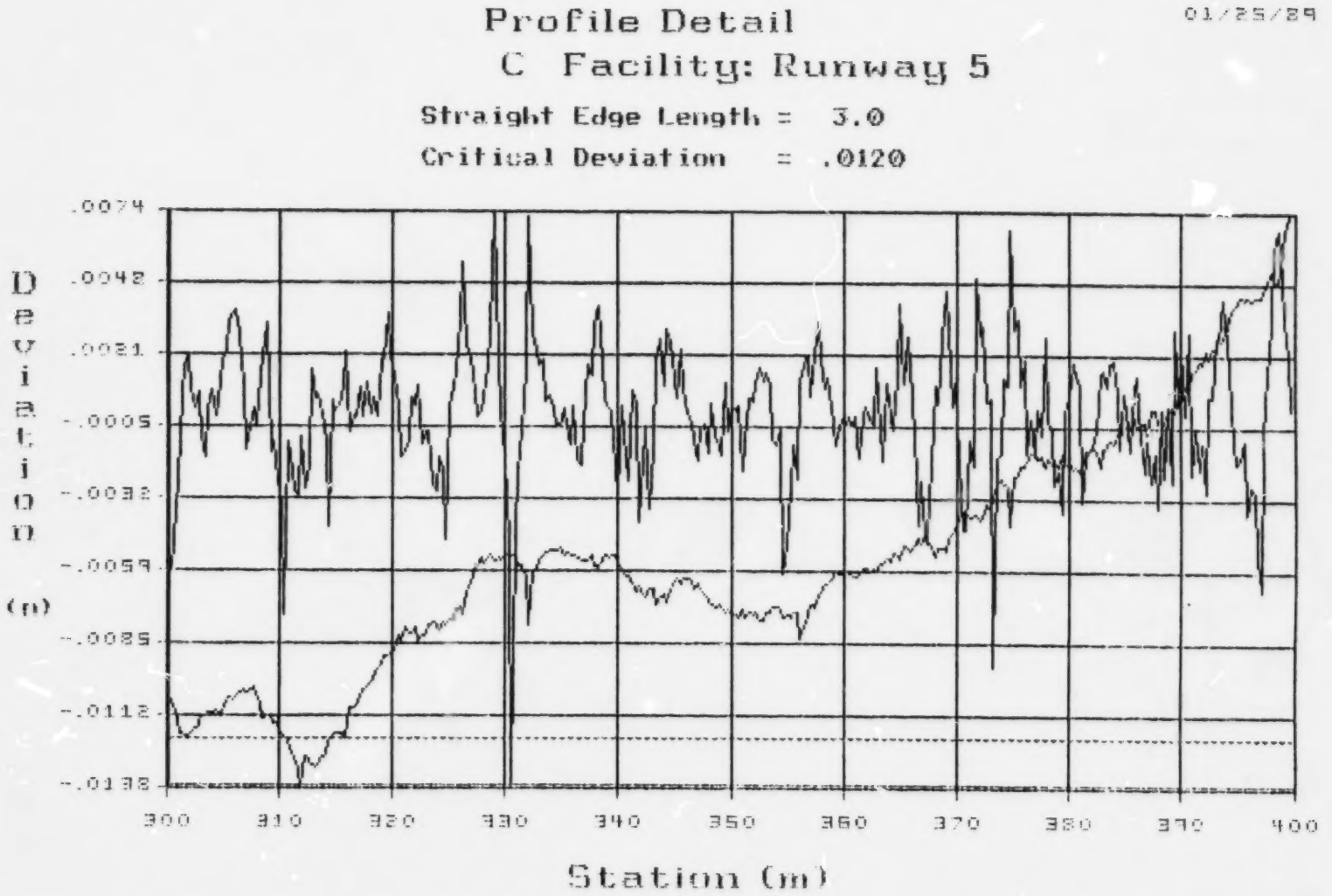

Profile Detail
01/25/89
C Facility: Runway 5
Straight Edge Length = 3.0
Critical Deviation = .0120
Deviation (in)
.0074
.0048
.0031
-.0005
-.0038
-.0059
-.0085
-.0112
-.0138
300
310
320
330
340
350
360
370
380
390
400
Station (m)

FIGURE 17

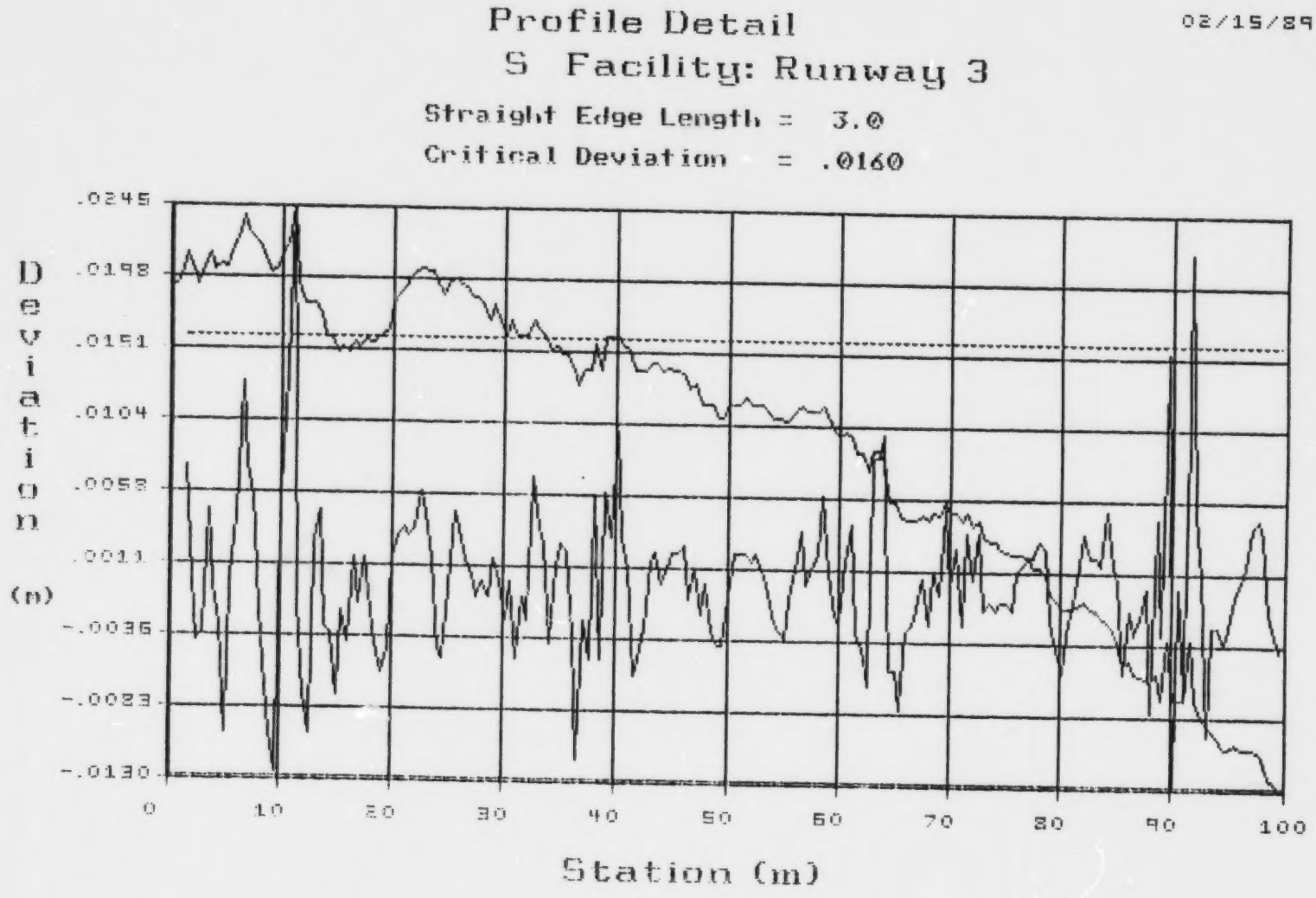
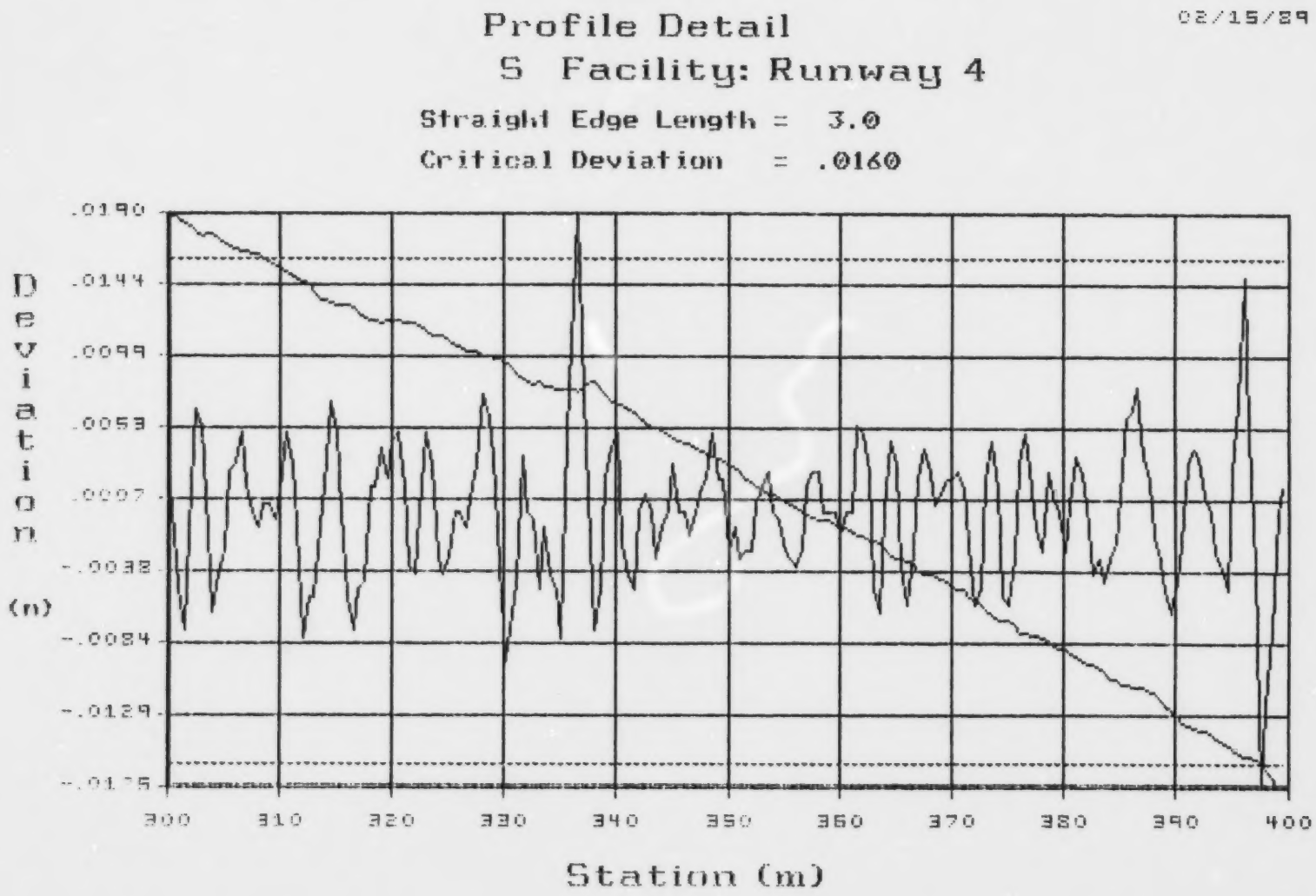

Profile Detail
02/15/89
S Facility: Runway 3
Straight Edge Length = 3.0
Critical Deviation = .0160
Deviation (in)
.0245
.0198
.0151
.0104
.0058
.0011
-.0036
-.0083
-.0130
0
10
20
30
40
50
60
70
80
90
100
Station (m)

FIGURE 18


Profile Detail
02/15/89
S Facility: Runway 4
Straight Edge Length = 3.0
Critical Deviation = .0160
.0190
.0144
.0099
.0053
.0007
-.0038
-.0084
-.0129
-.0175
Deviation (m)
300
310
320
330
340
350
360
370
380
390
400
Station (m)

6. CONCLUSIONS

Based on the survey on the state of the art of determining pavement roughness and the analysis completed in this report, the Surface Profile/Travelling Straight Edge (SP/TSE), Root Mean Square Vertical Acceleration (RMSVA) and International Roughness Index procedures are proven methods of analyzing pavement roughness from profile elevation data. The SP/TSE for a straight edge length of 3.0 metres appears to be the most appropriate method of identifying specific high amplitude events that are of primary concern when analyzing airport pavement roughness. The IRI appears to be the most appropriate statistic for use in comparing pavement roughness and equipment on an international basis, recognizing that the World Bank has expended significant effort to promote its use as a 'standard'. The Ottawa test sections monitored during the field correlation study clearly demonstrate that roughness measurement techniques can be correlated to each other. However, it is also clear that the Class 3 devices (PURD and Maysmeter) and Class 4 surveys (RCI) are less precise than Class 1 assessments obtained using Dipstick® or precise rod and level surveys, and result in much lower correlation coefficients for the sections studied.

The Runway Roughness Analysis Program (R-RAP) computer software developed for this project enables Transport Canada to calculate SP/TSE, RMSVA and IRI pavement roughness statistics directly from pavement profile elevation data.

7. RECOMMENDATIONS

It is strongly recommended that Transport Canada runway roughness evaluation and pavement profile elevation measurement be completed using only IRRE Class 1 methods. The Digital Incremental Profiler (Dipstick^{R}) appears to be the most economical Class 1 survey device currently available, with precise rod and level surveys (Invar staves) also used for this level of accuracy. The lack of consistent and acceptable correlation coefficients for data obtained using the common Maysmeter and PURD devices strongly supports this report's recommendation and the findings of the IRRE. The high level of safety required for the airport runways dictates that this work be completed using the most precise methods.

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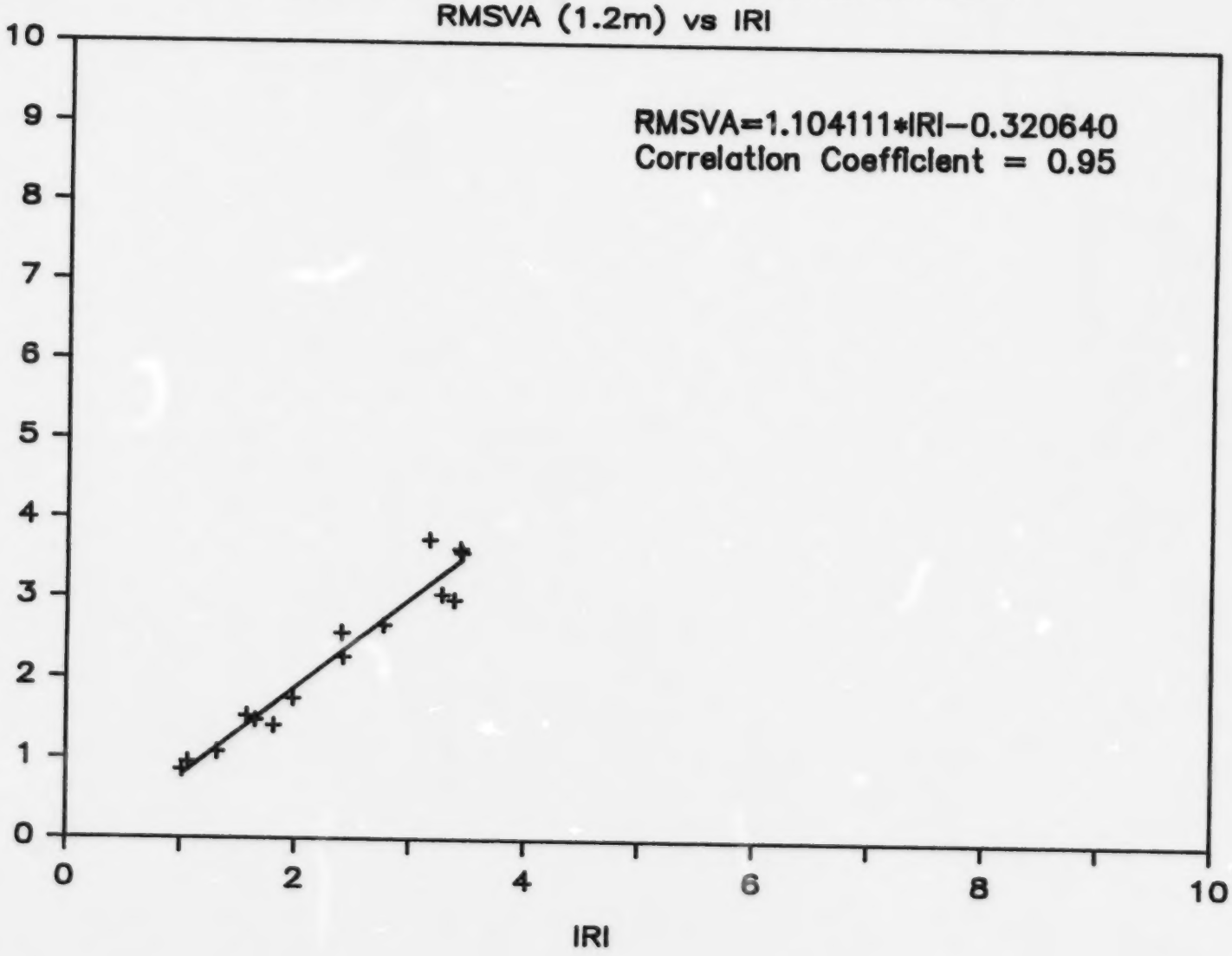
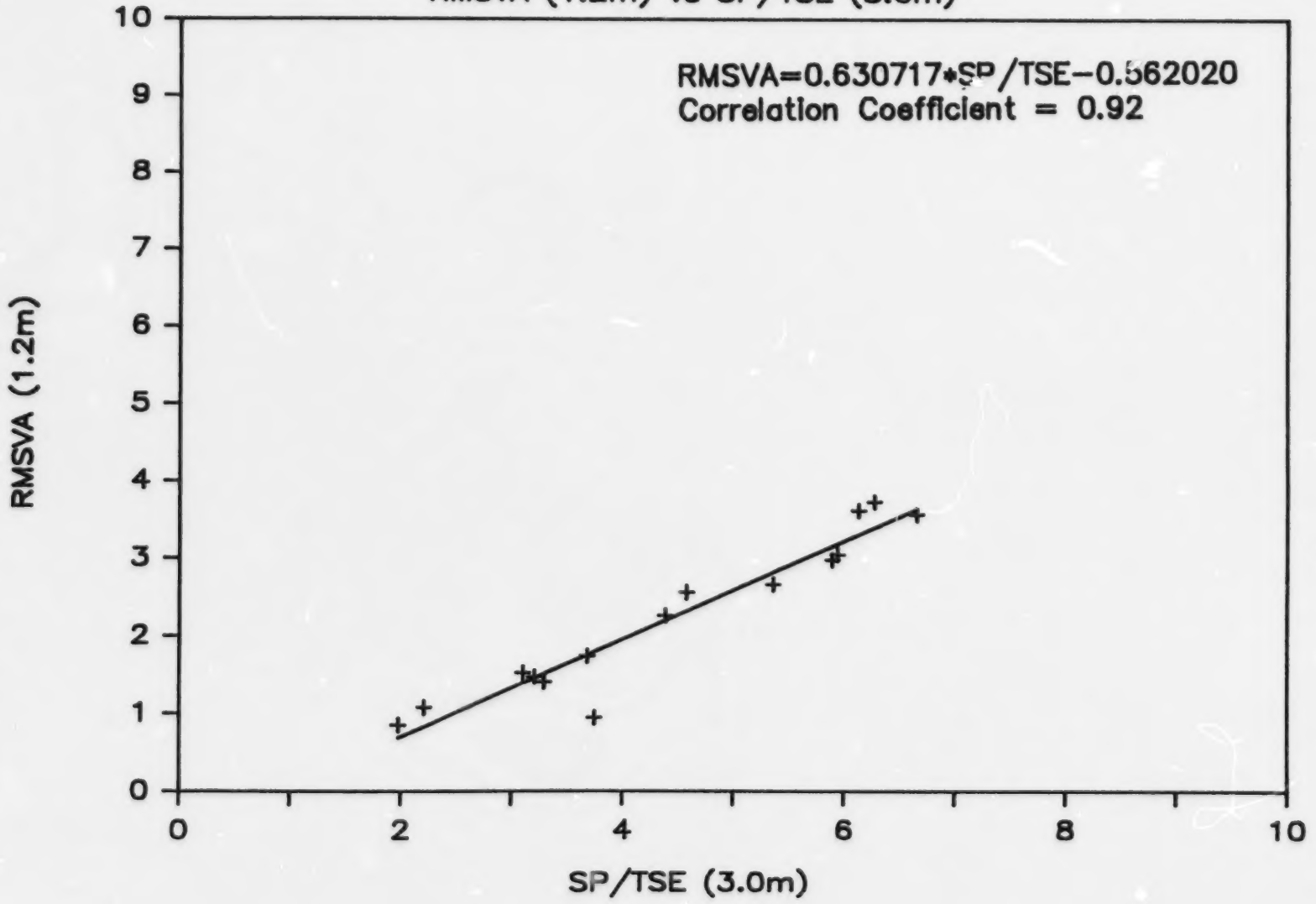
APPENDIX A

Correlation Data Regression Curves

ROUGHNESS CORRELATION



ROUGHNESS CORRELATION



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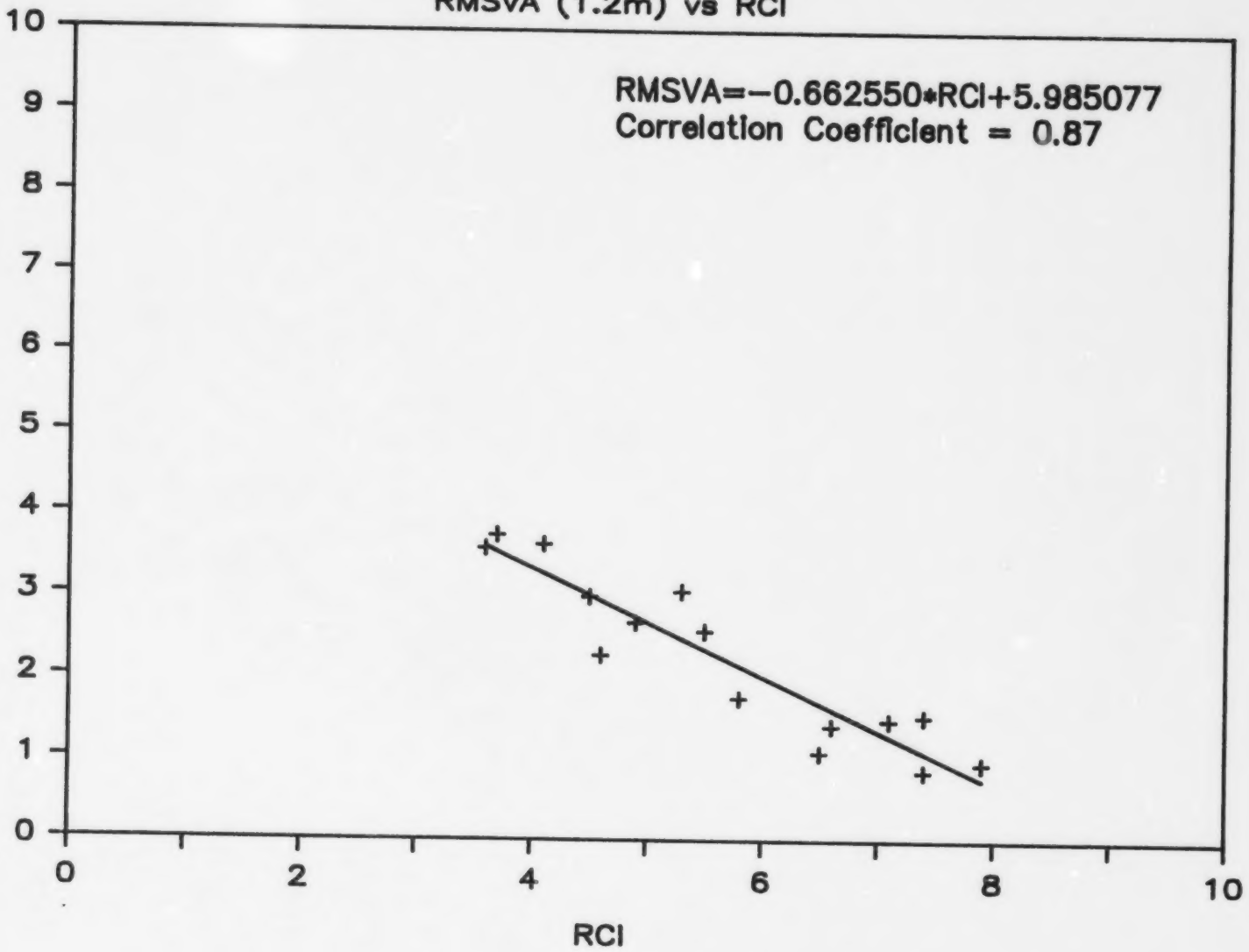

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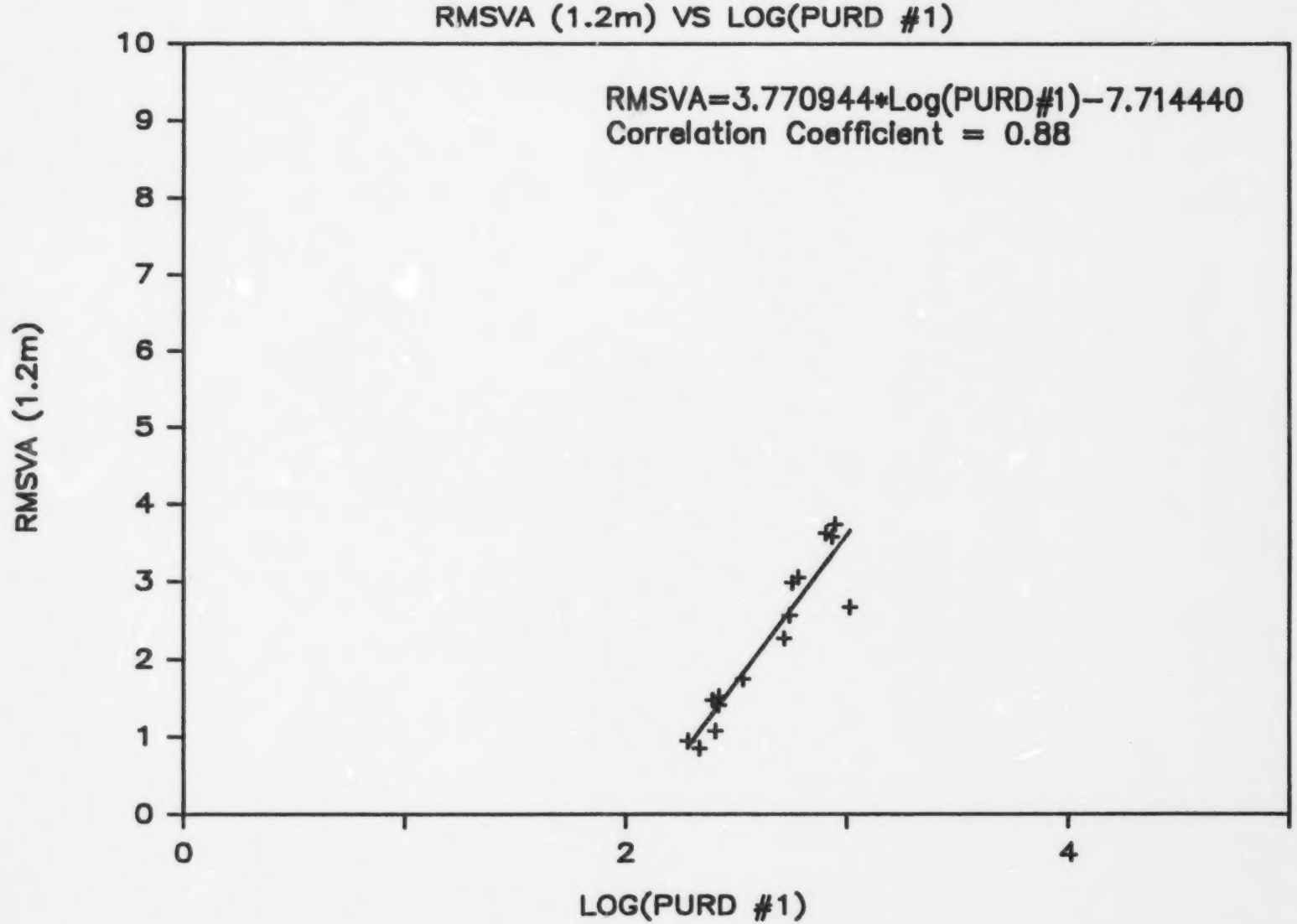

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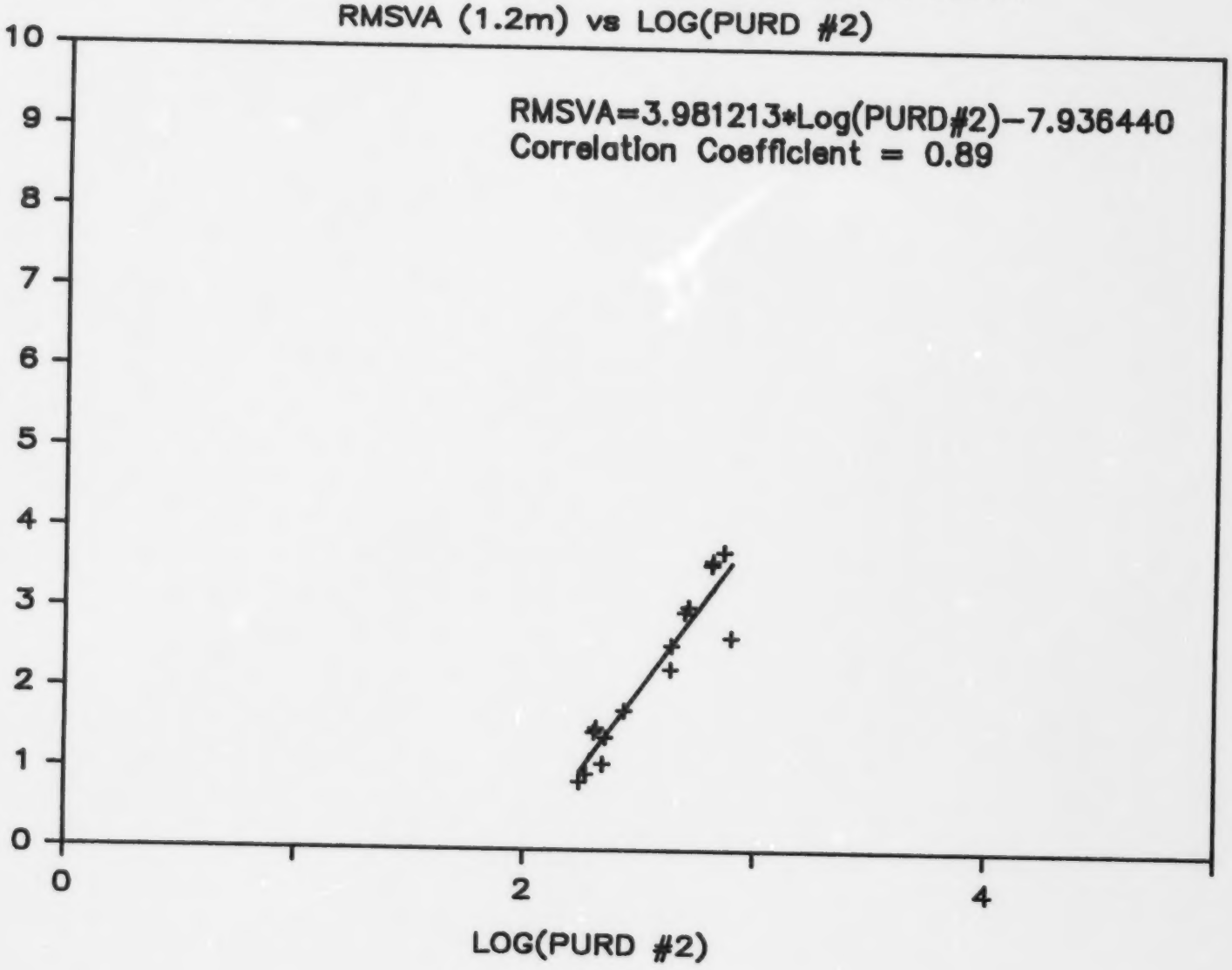

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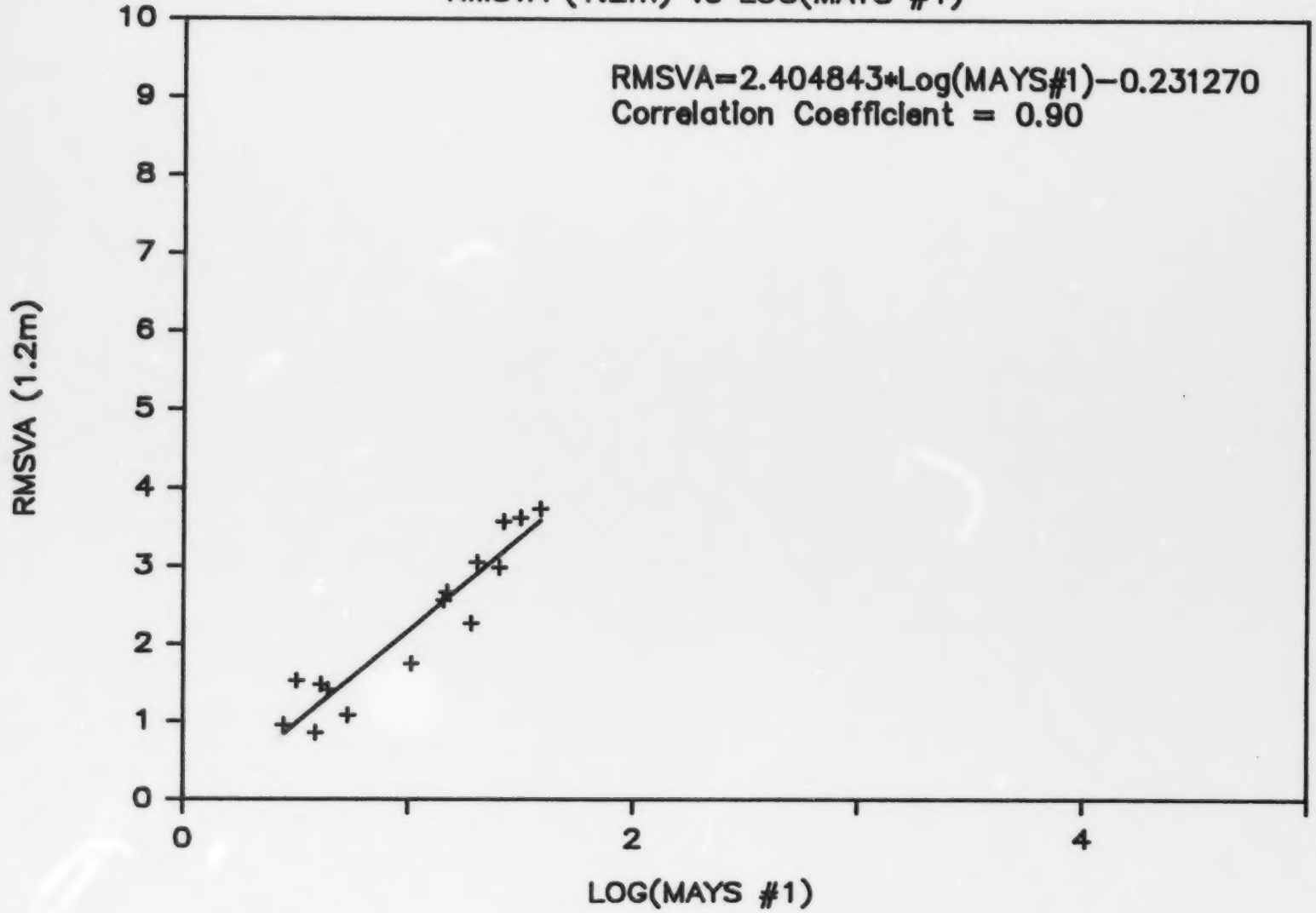

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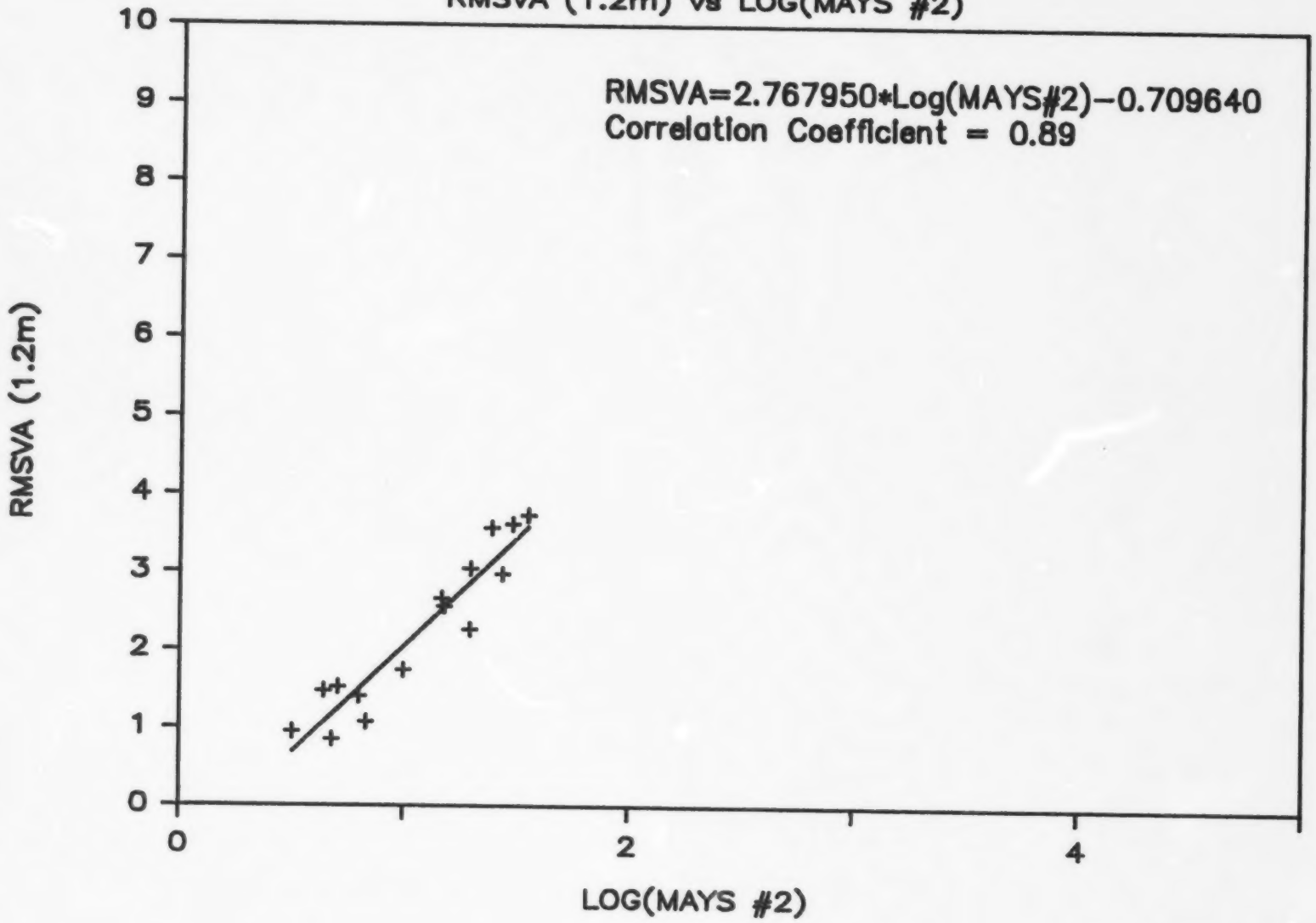

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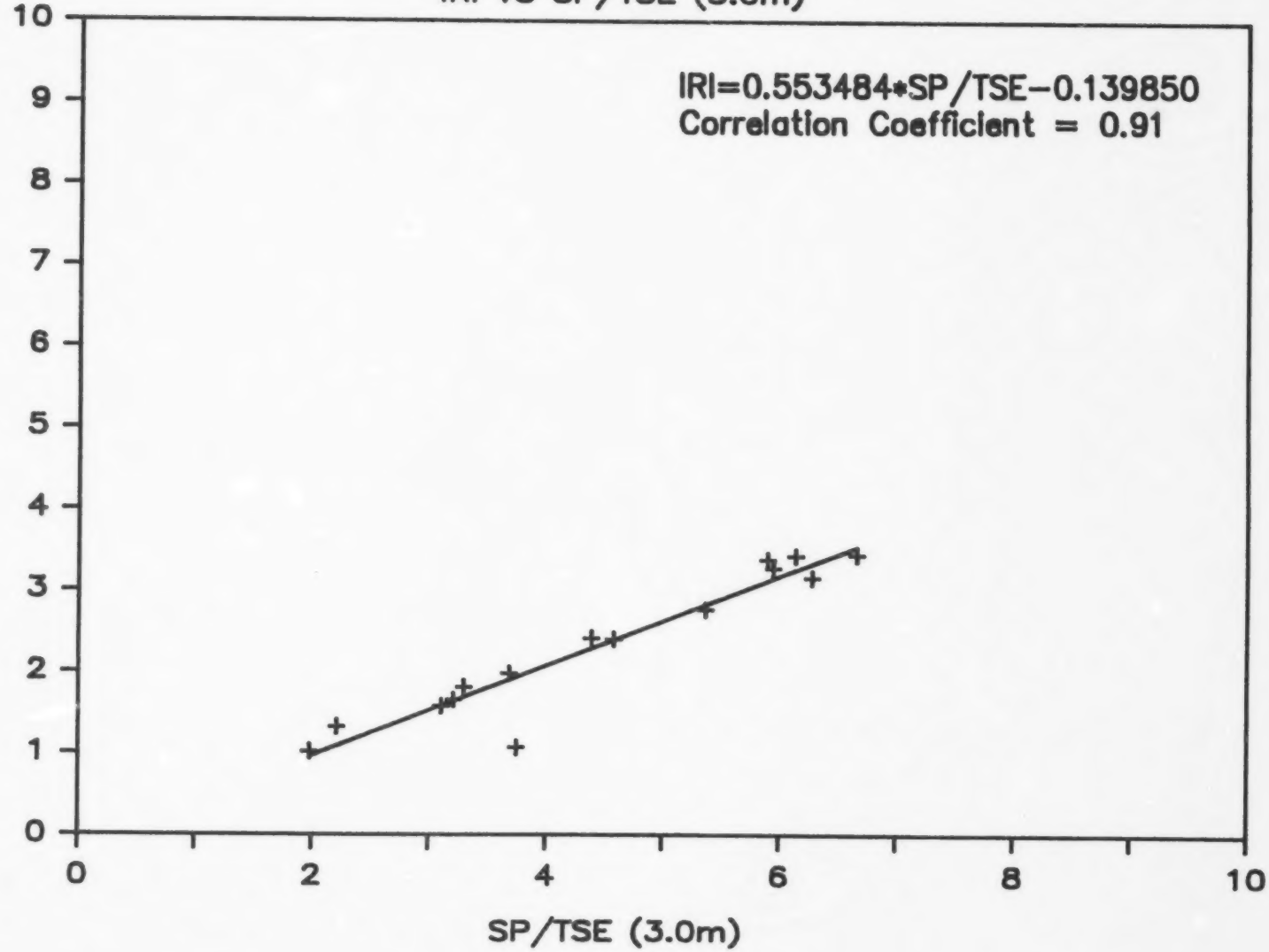

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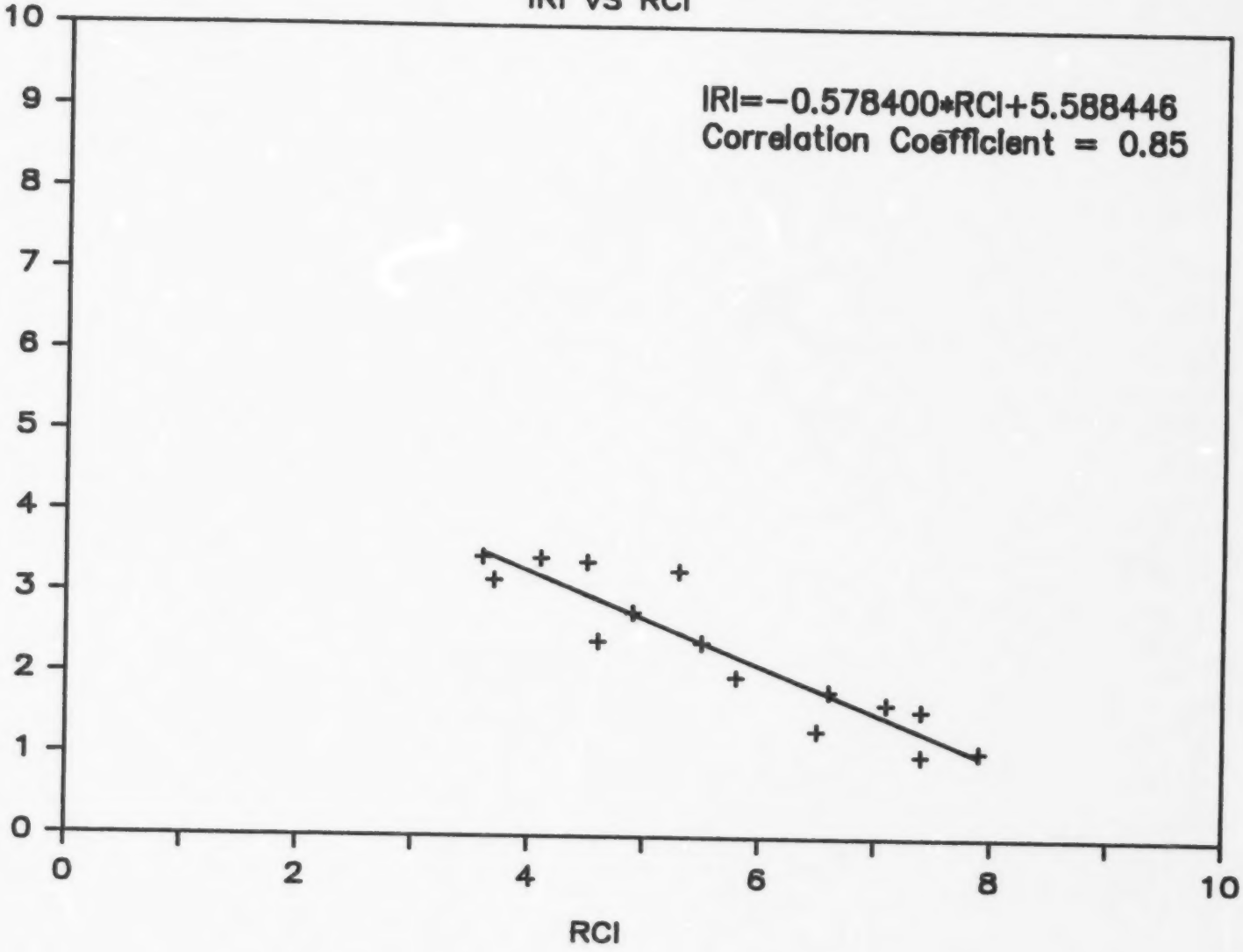

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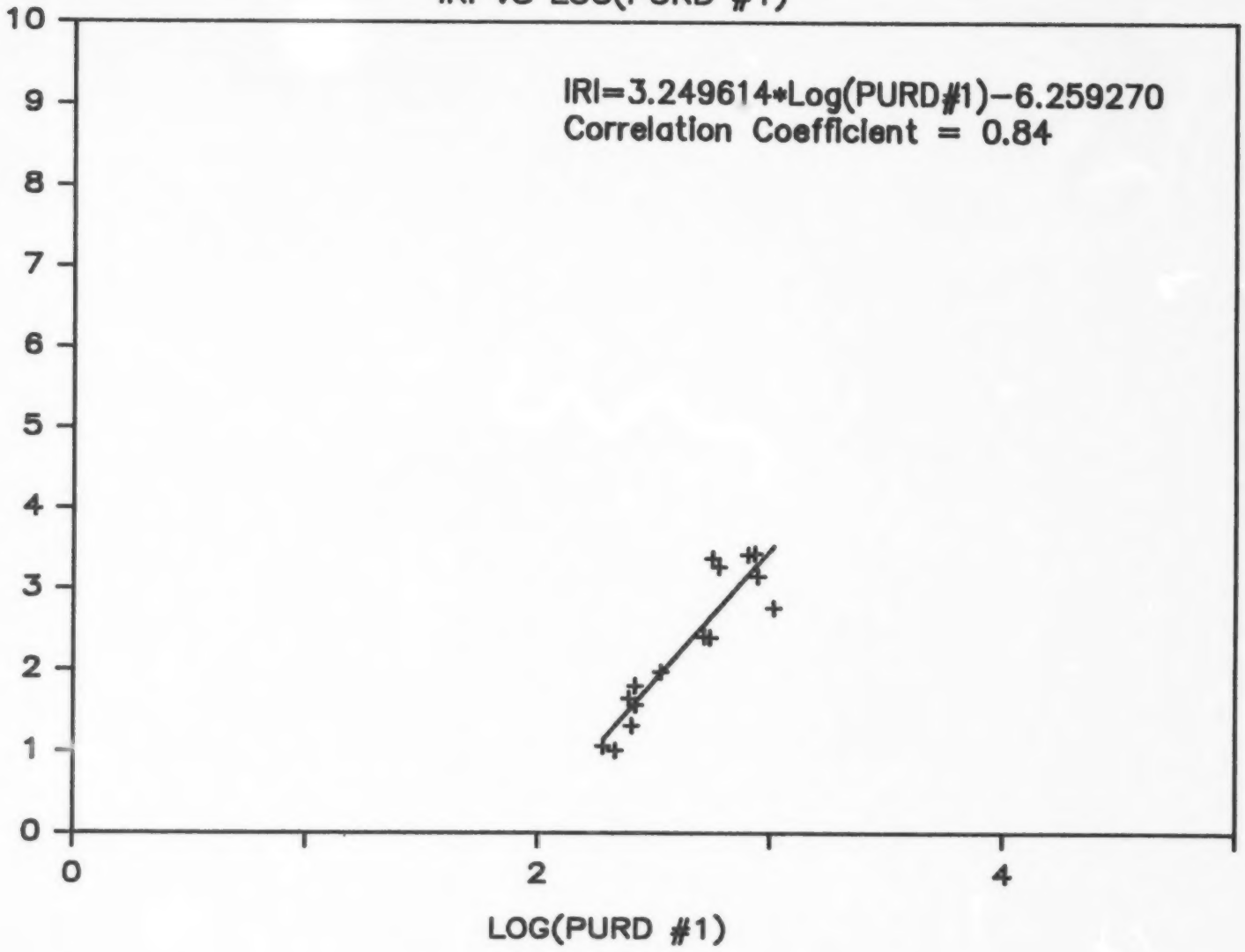

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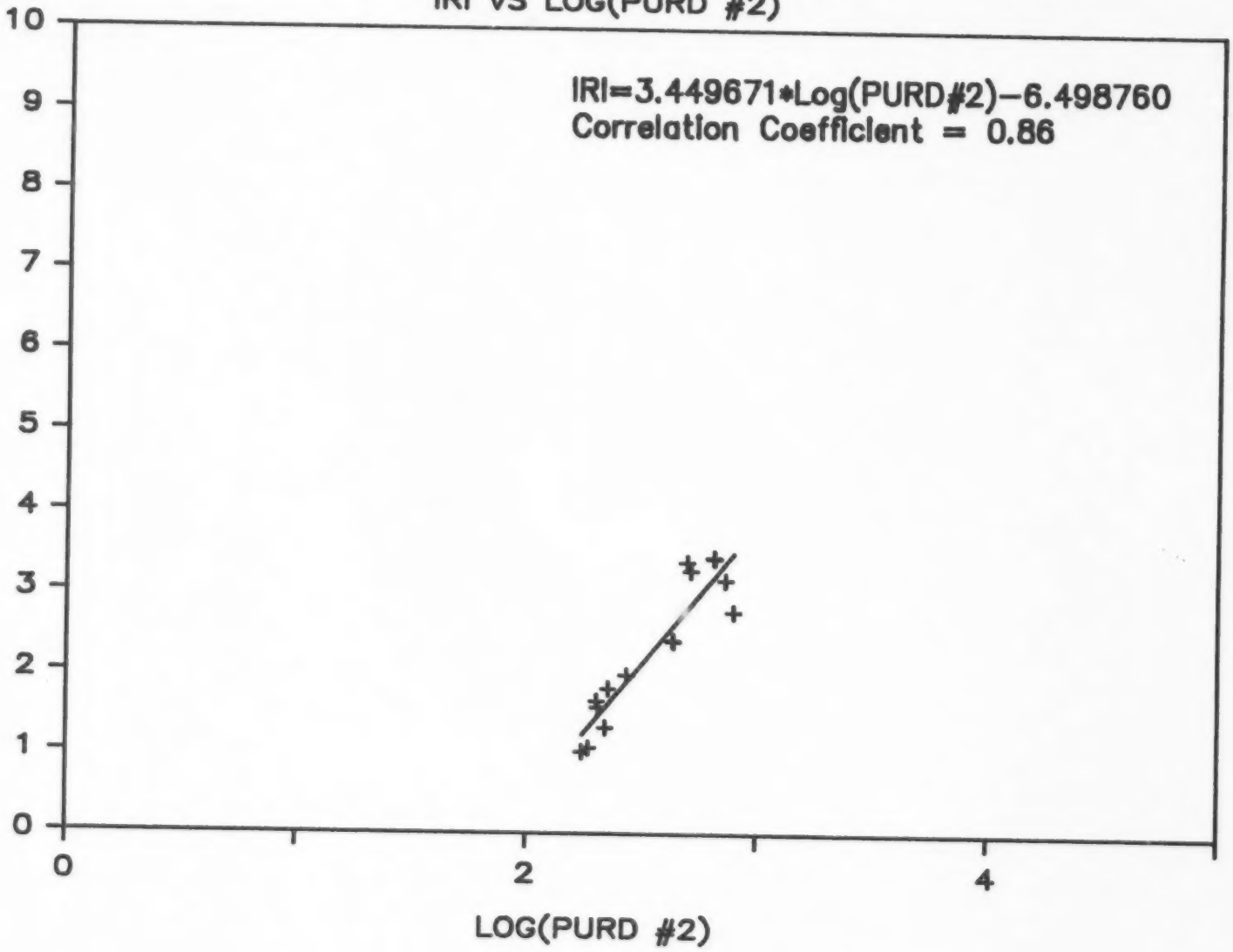

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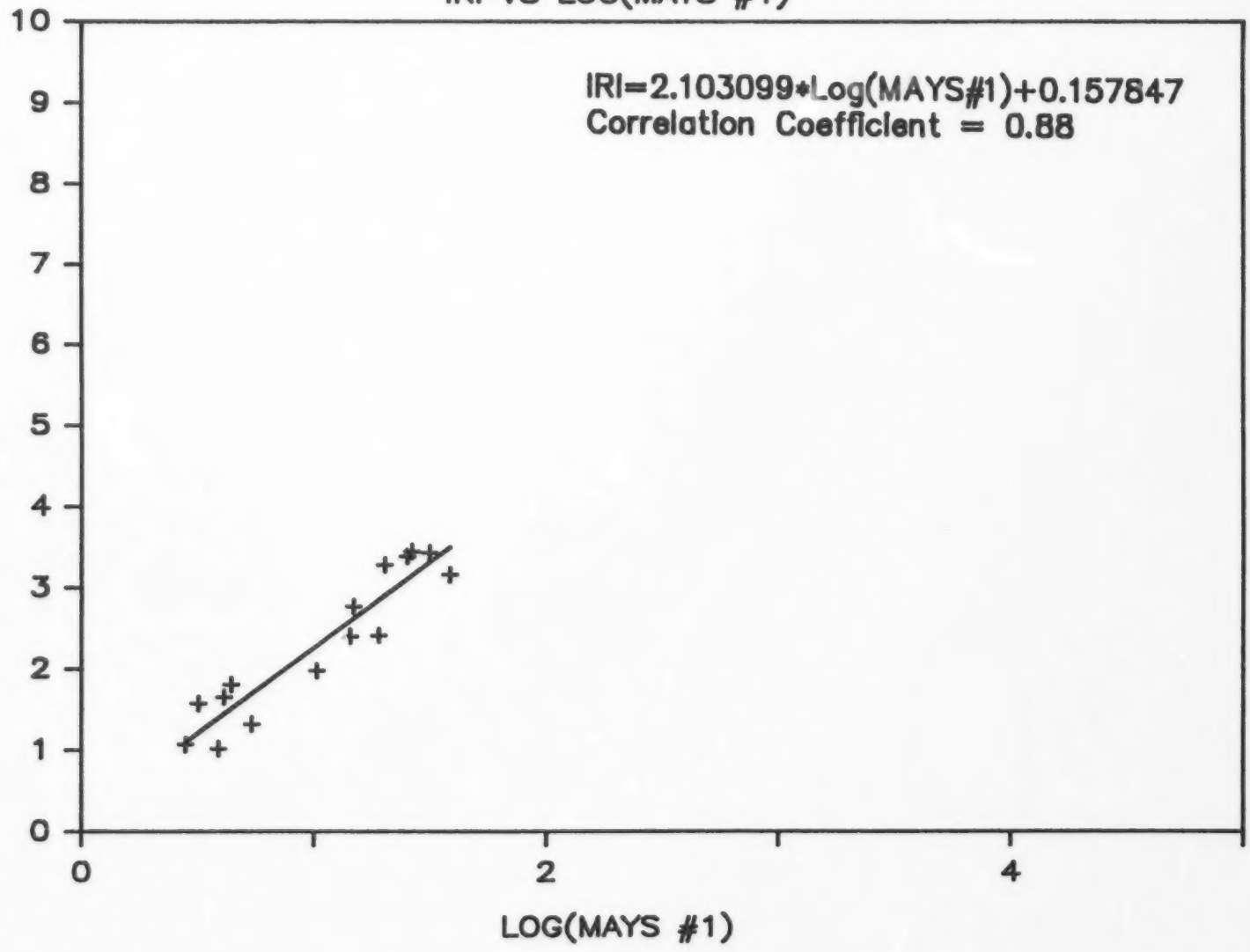

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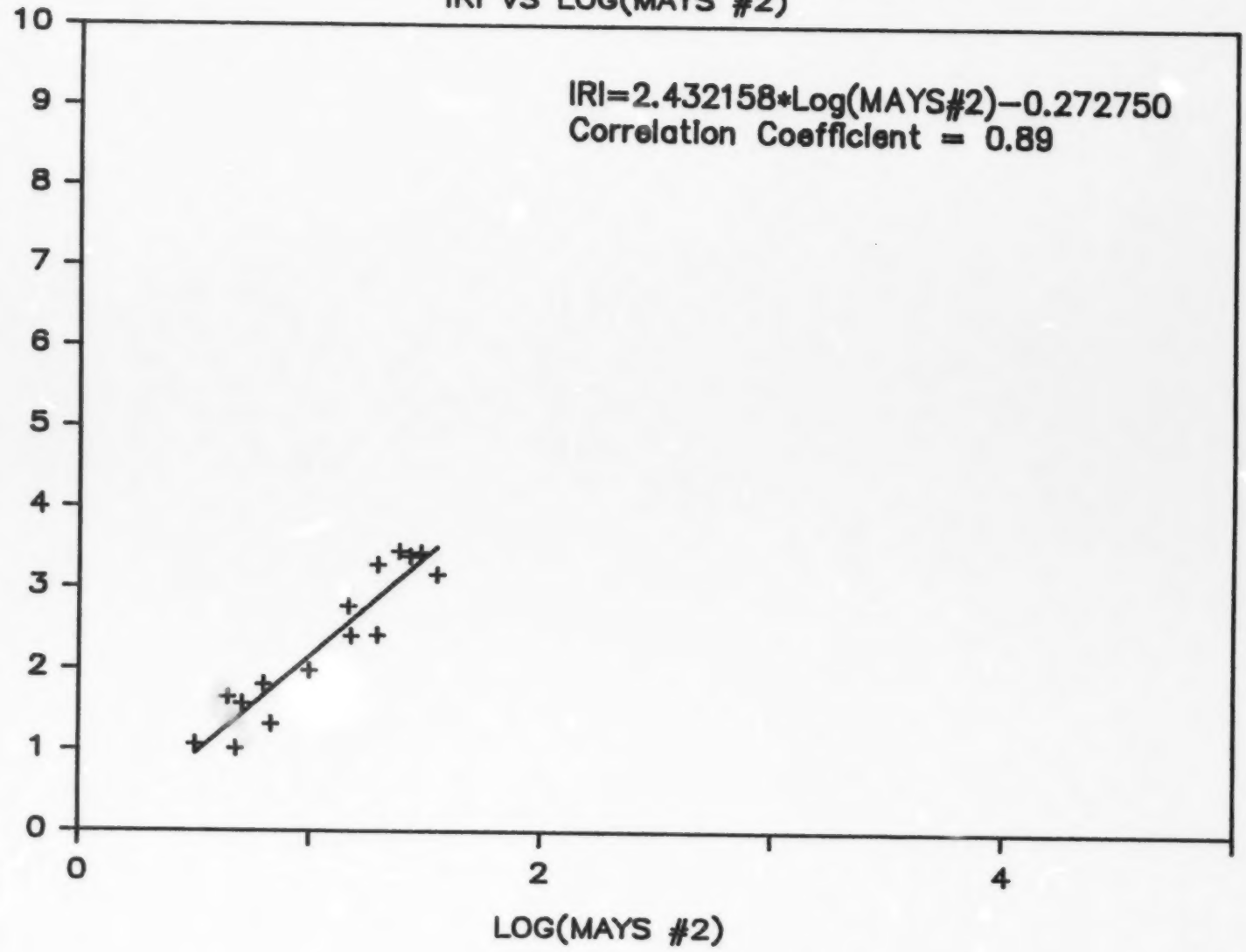

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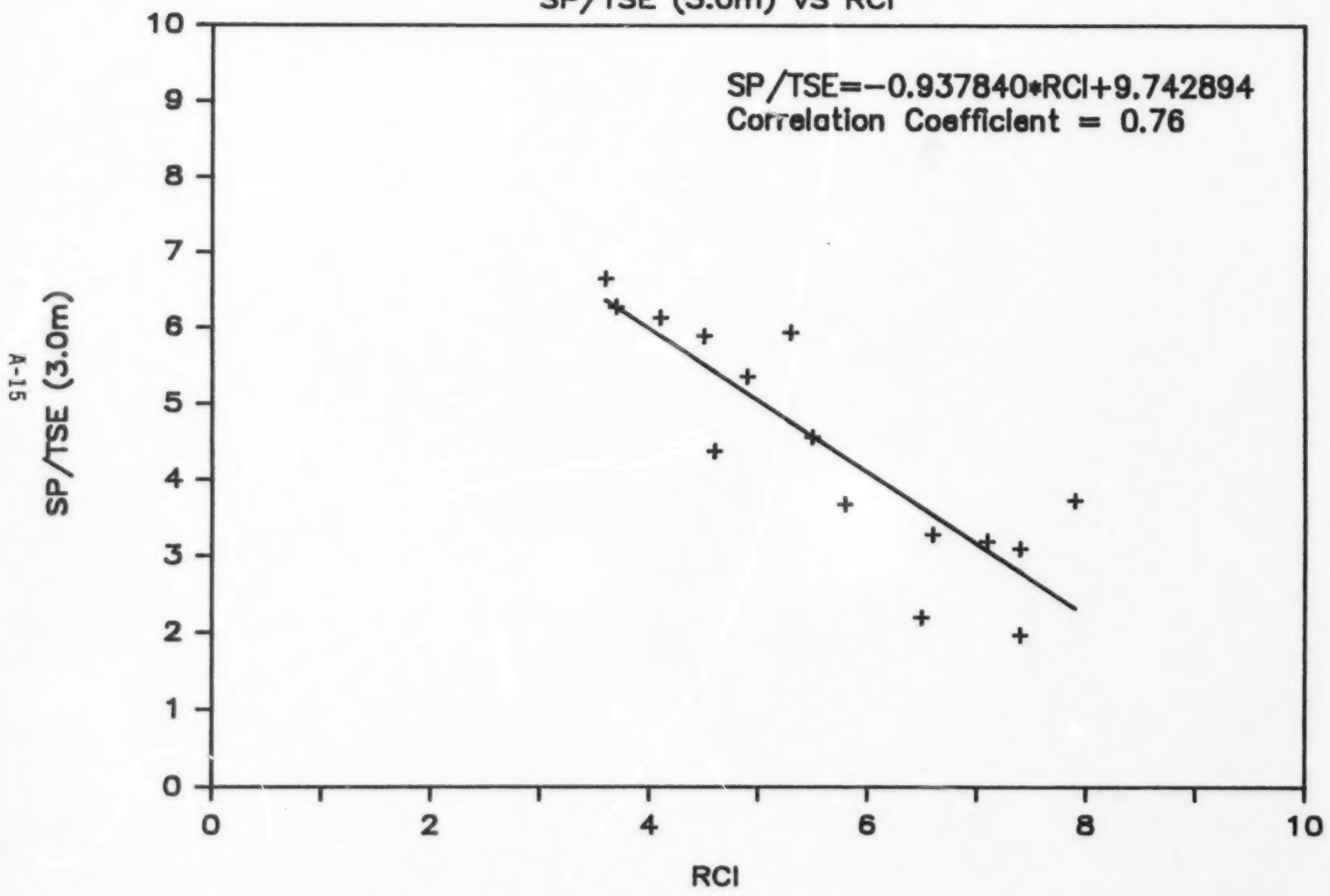

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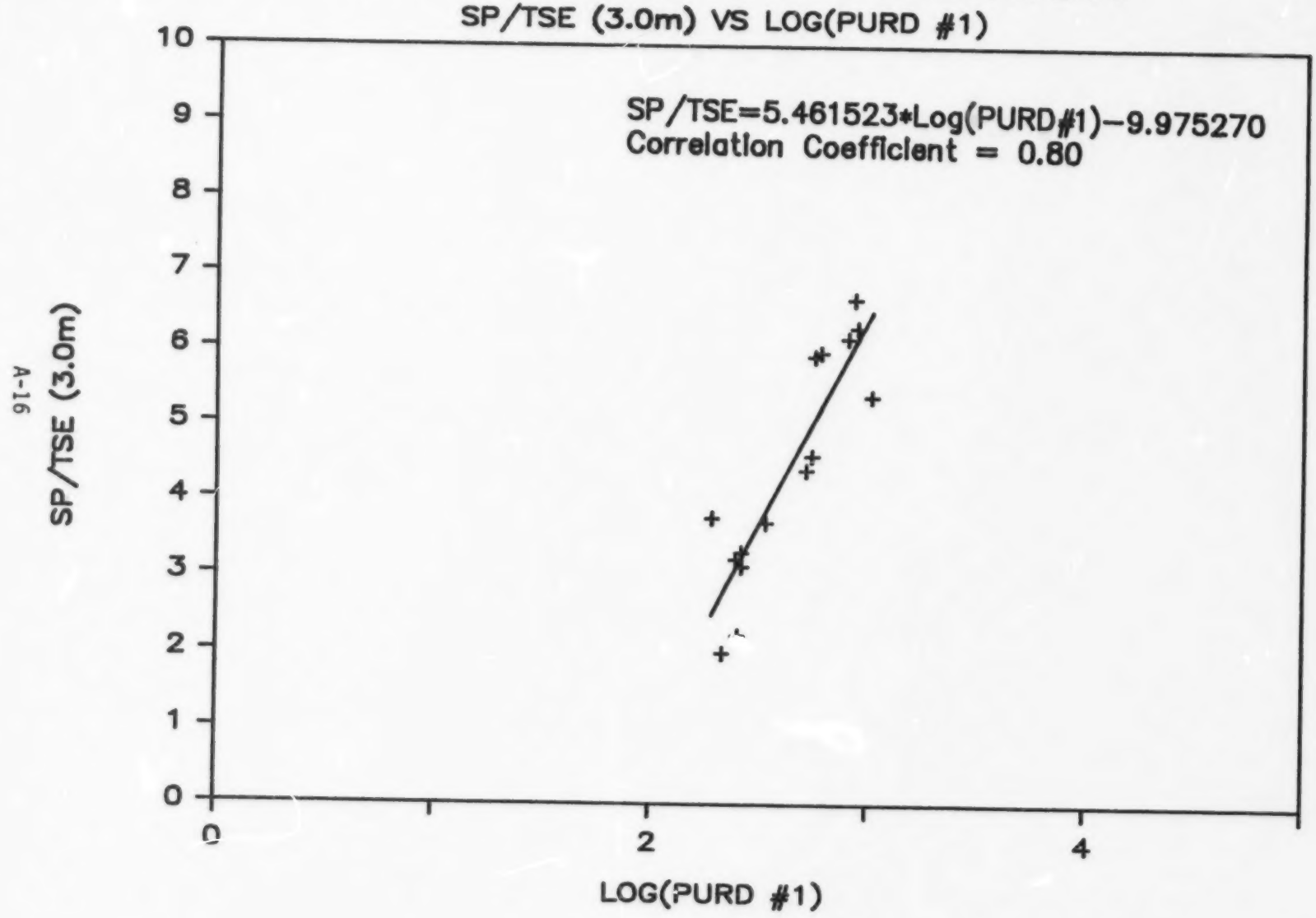

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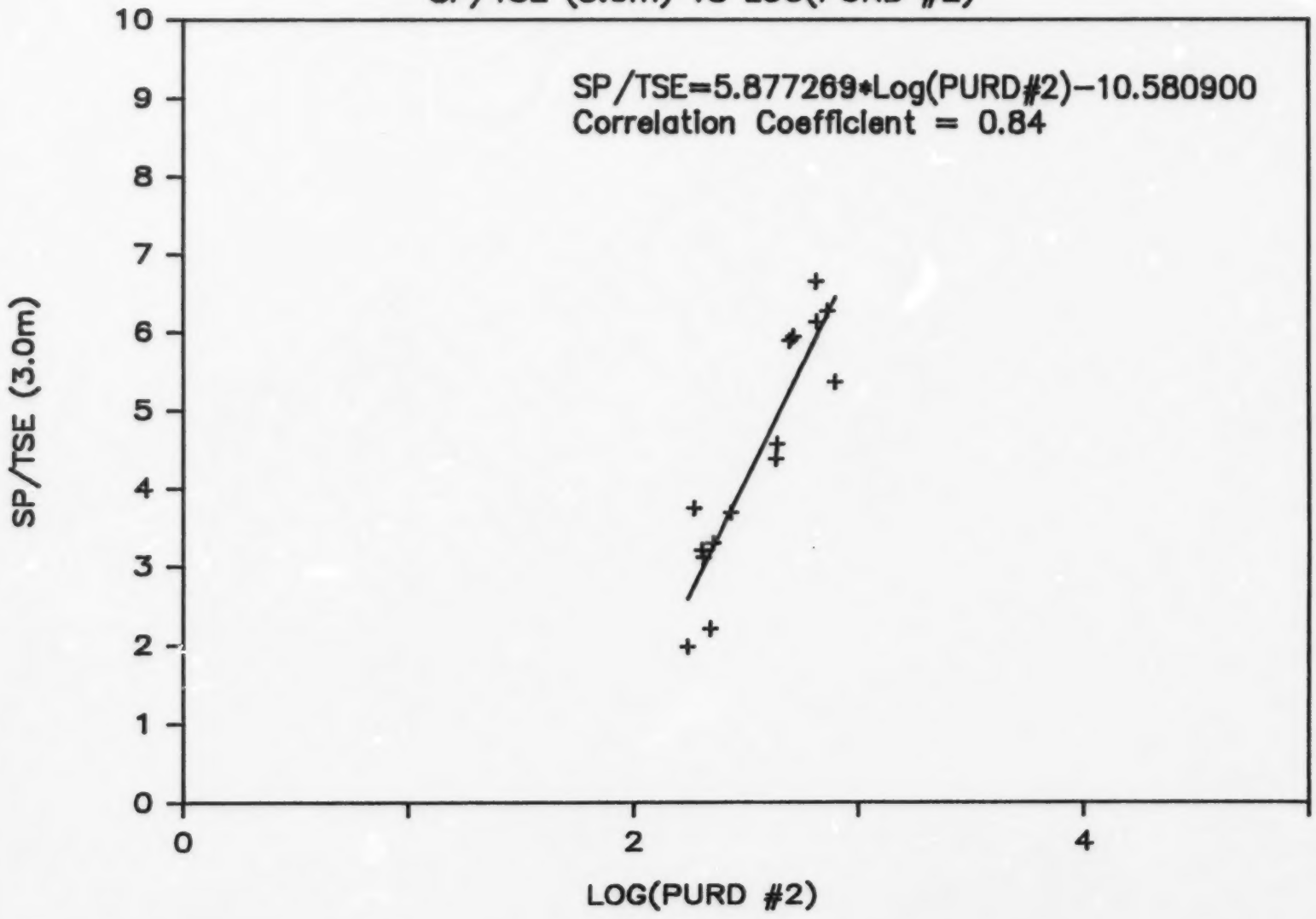

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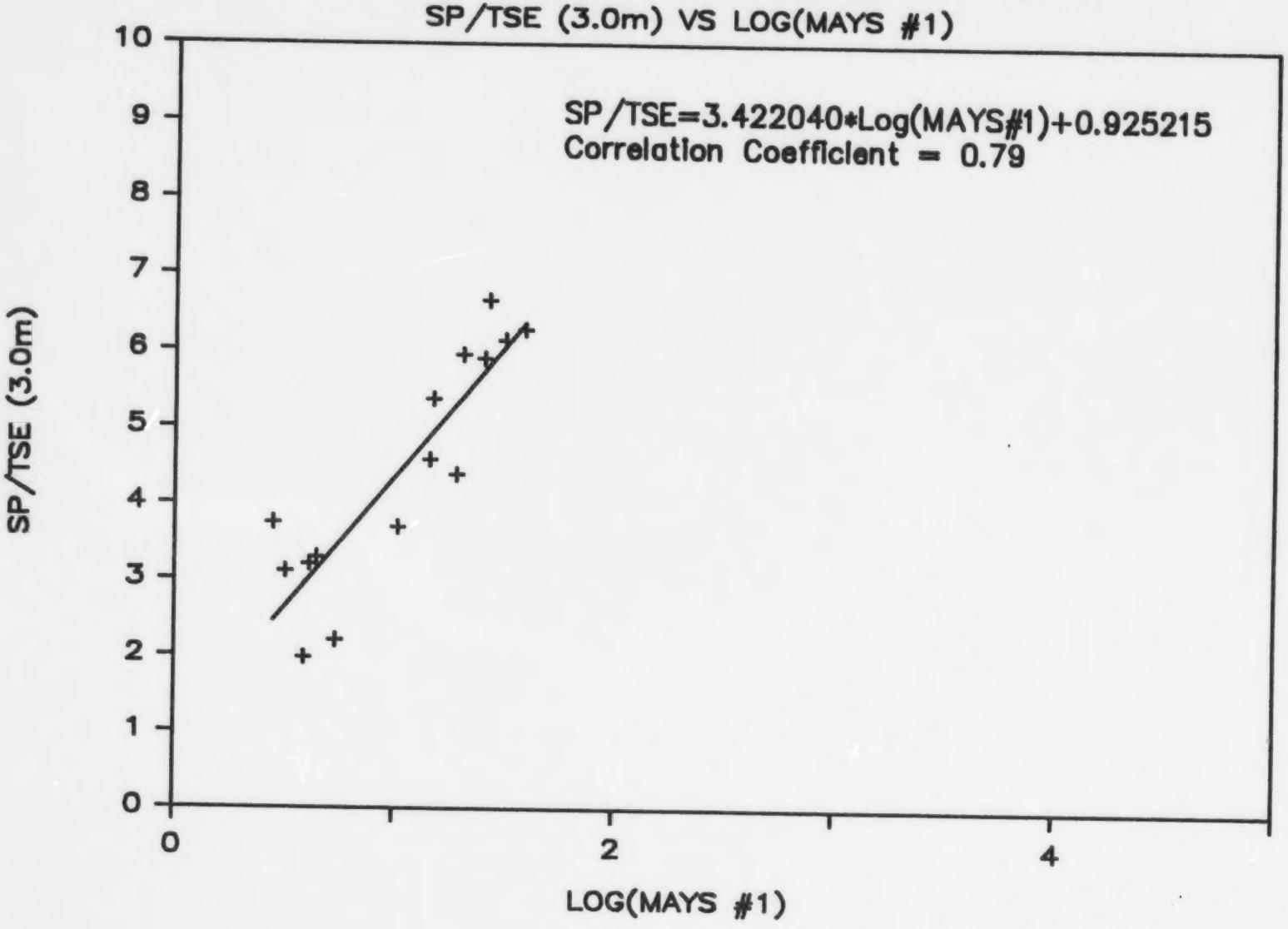
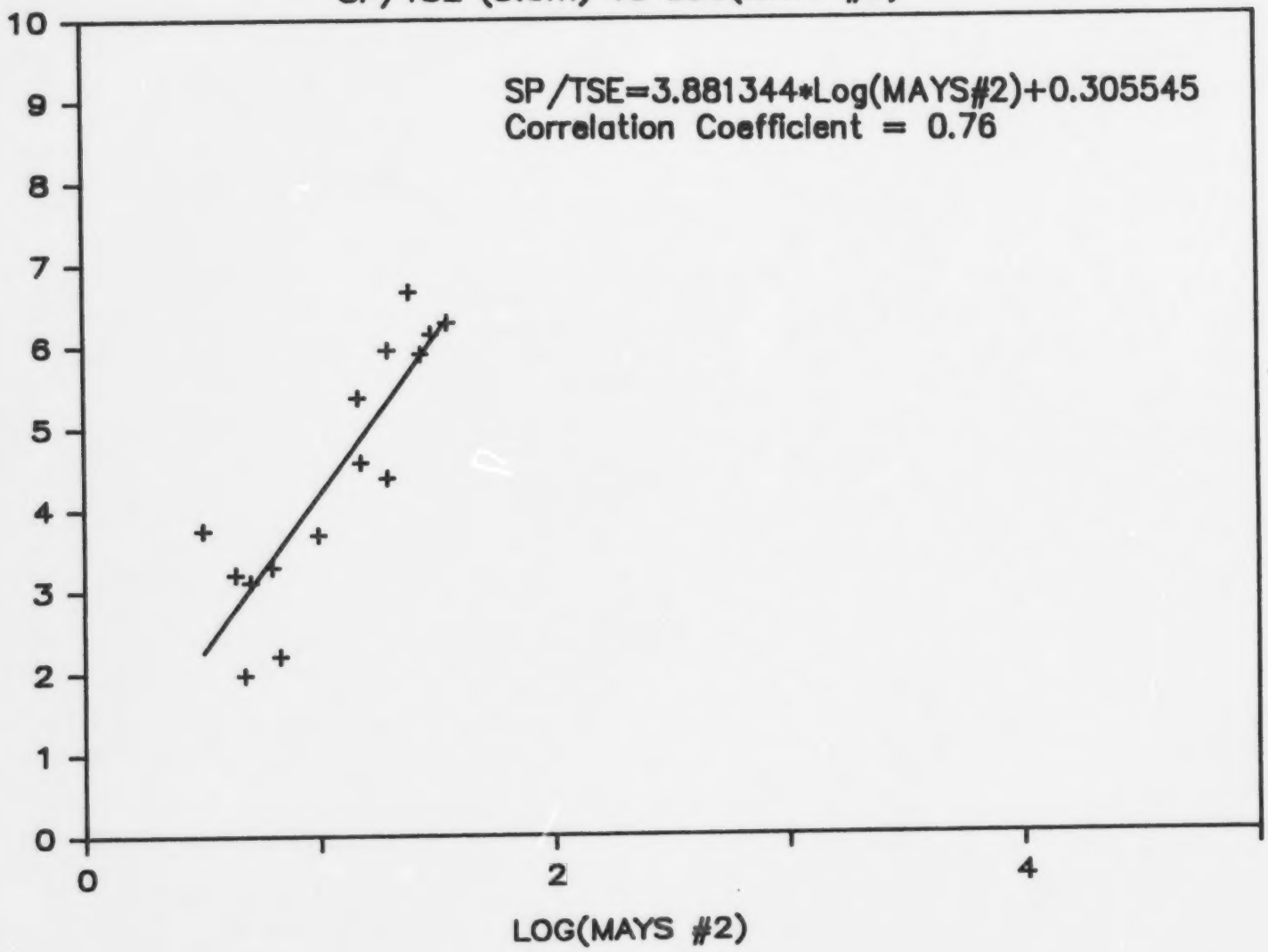


ROUGHNESS CORRELATION

SP/TSE (3.0m) VS LOG(MAYS #2)



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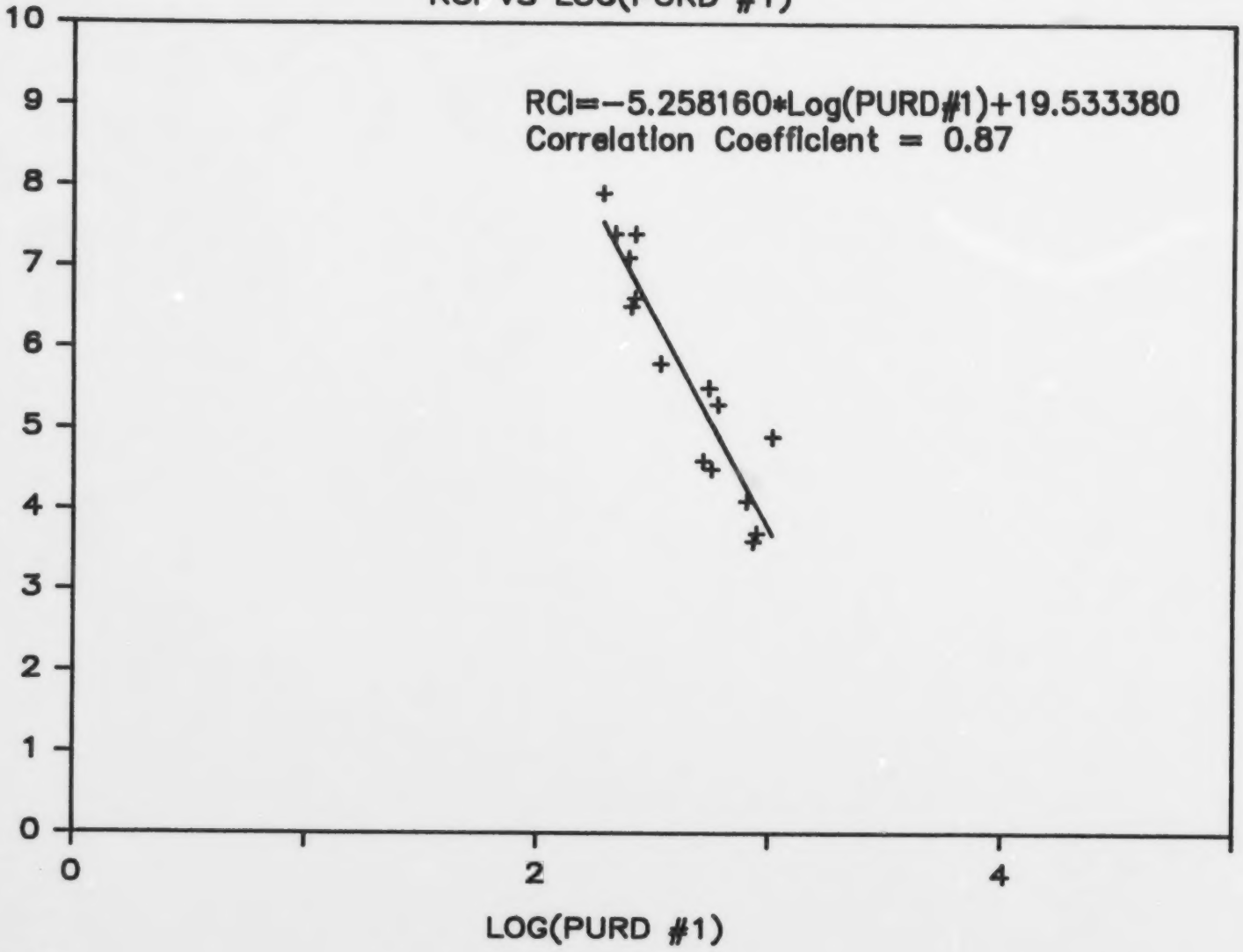

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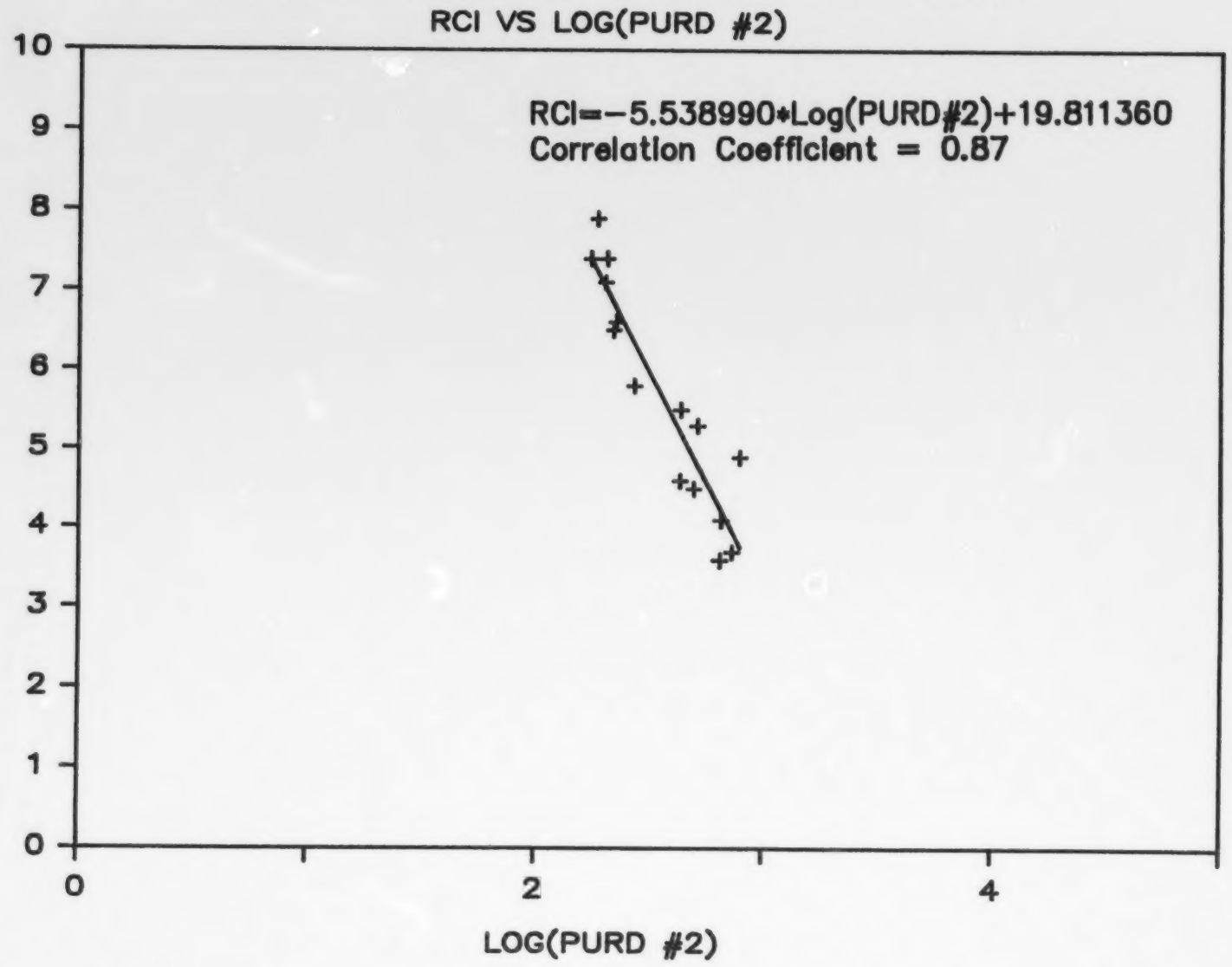

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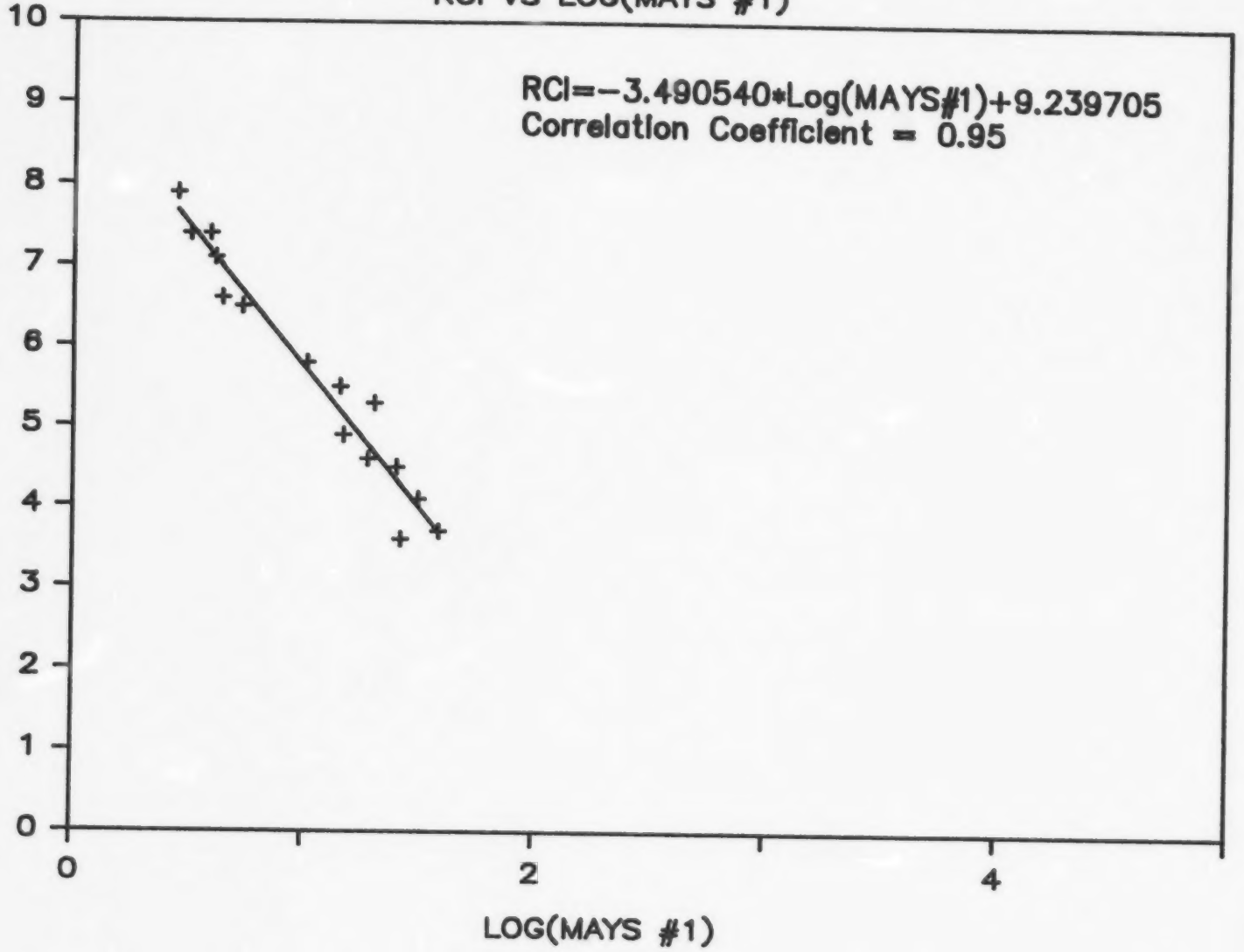

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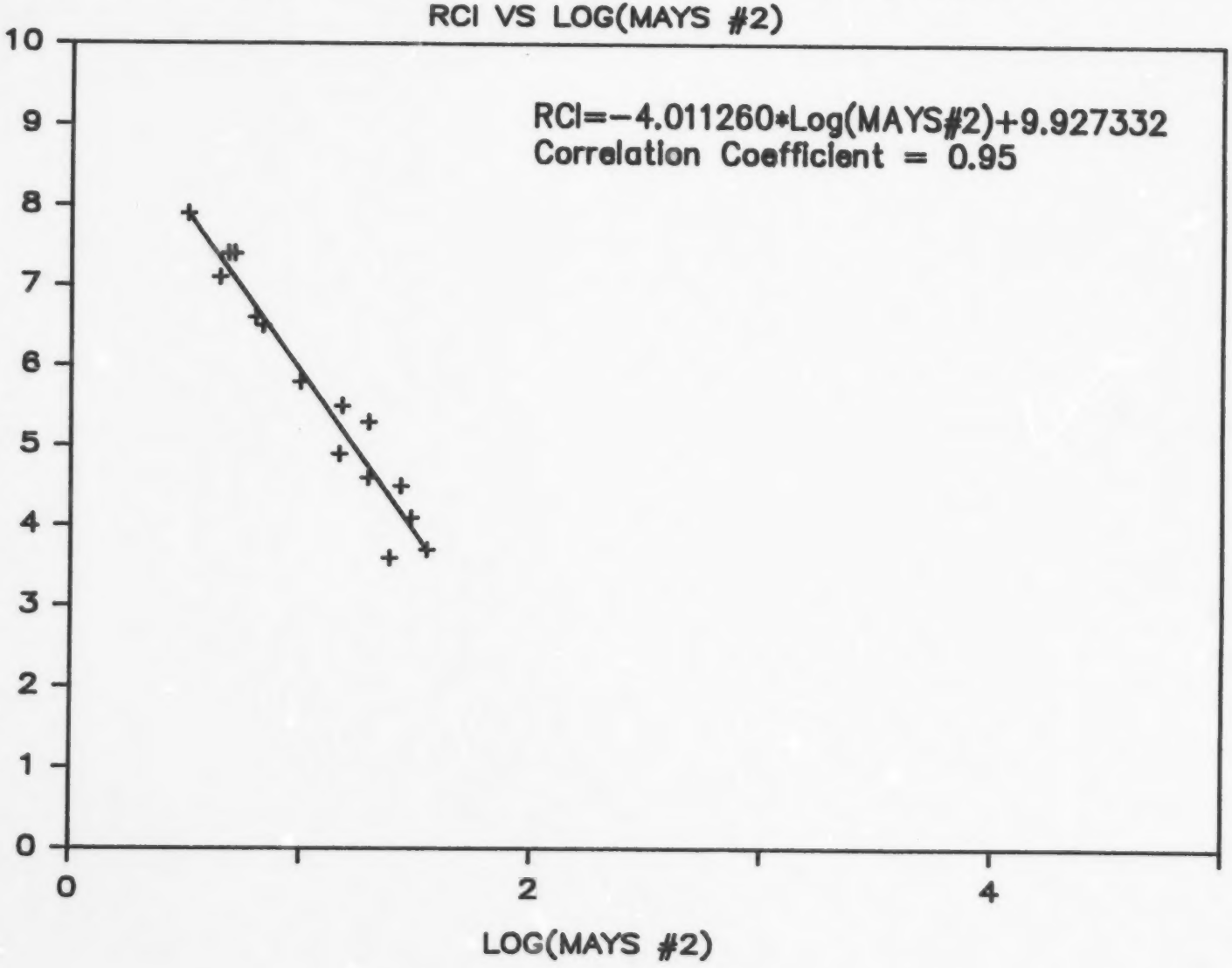

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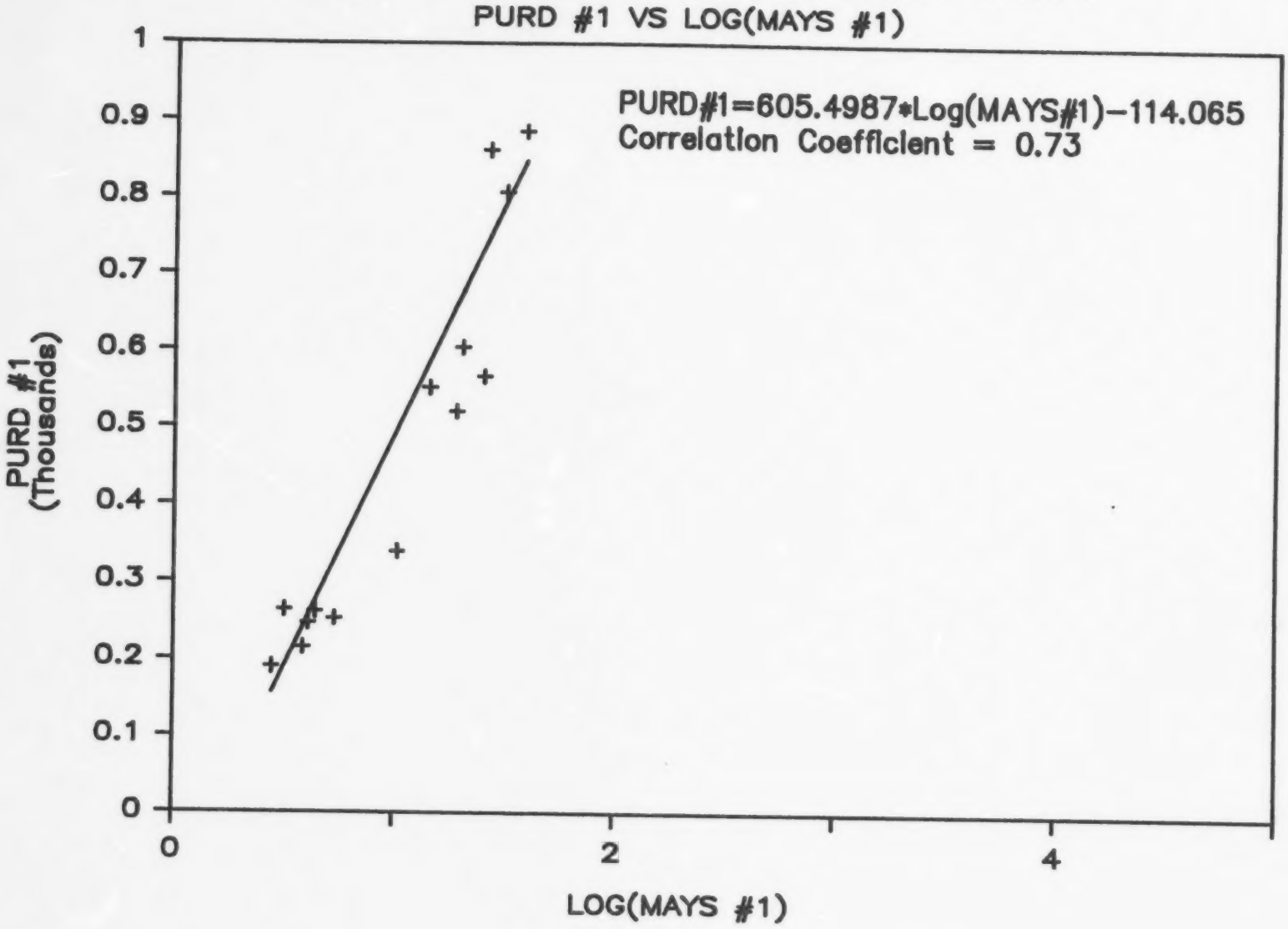

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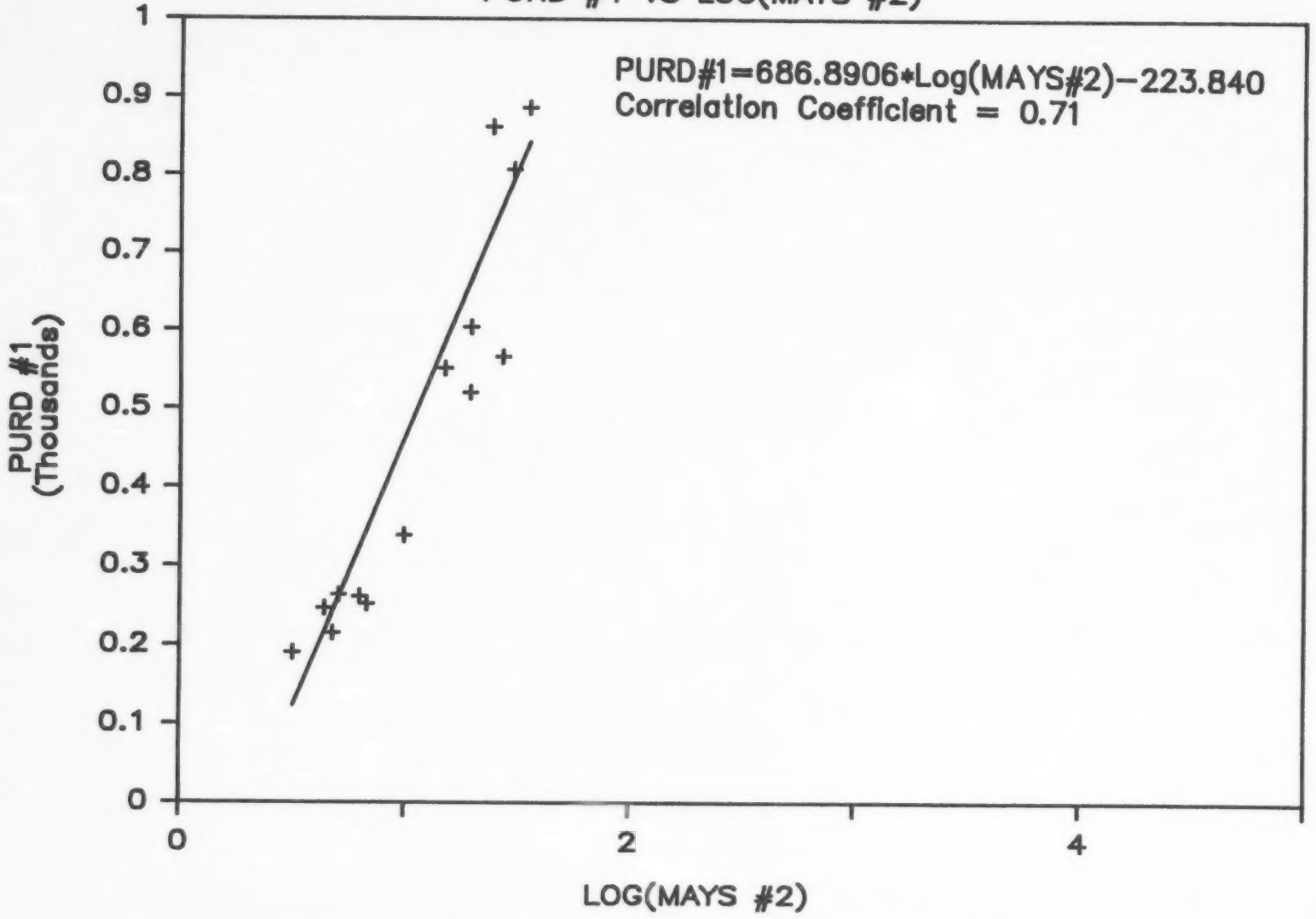

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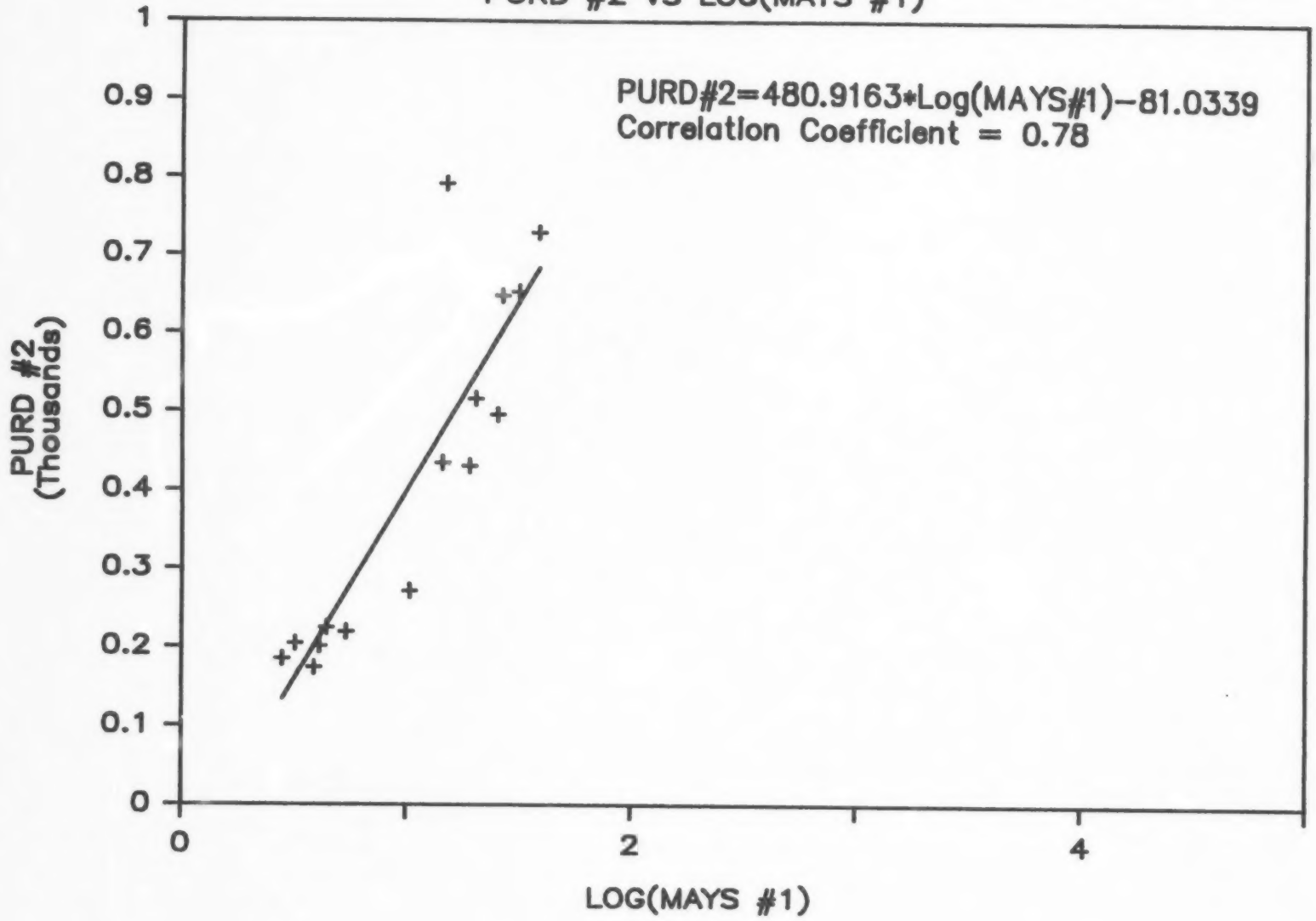
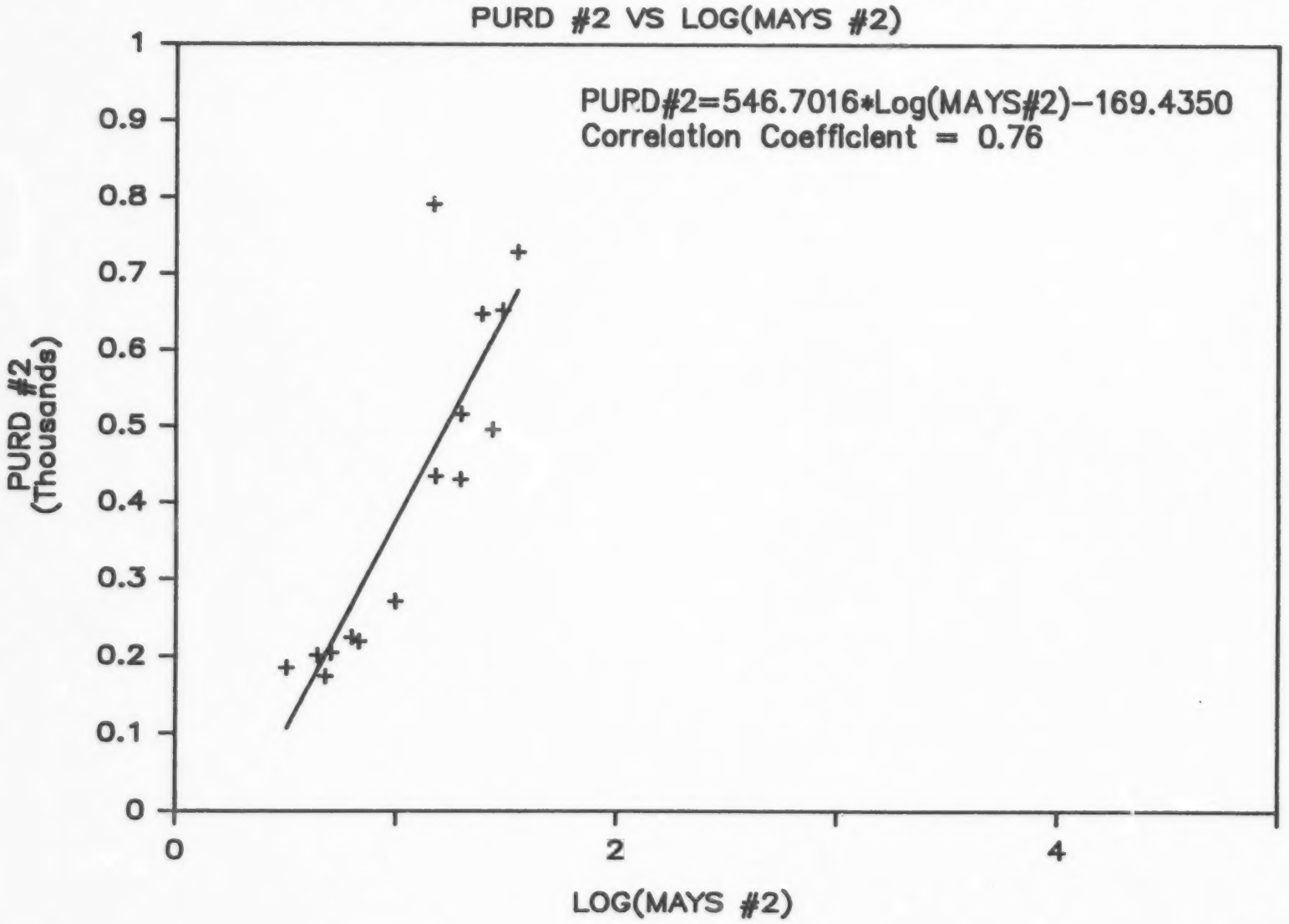
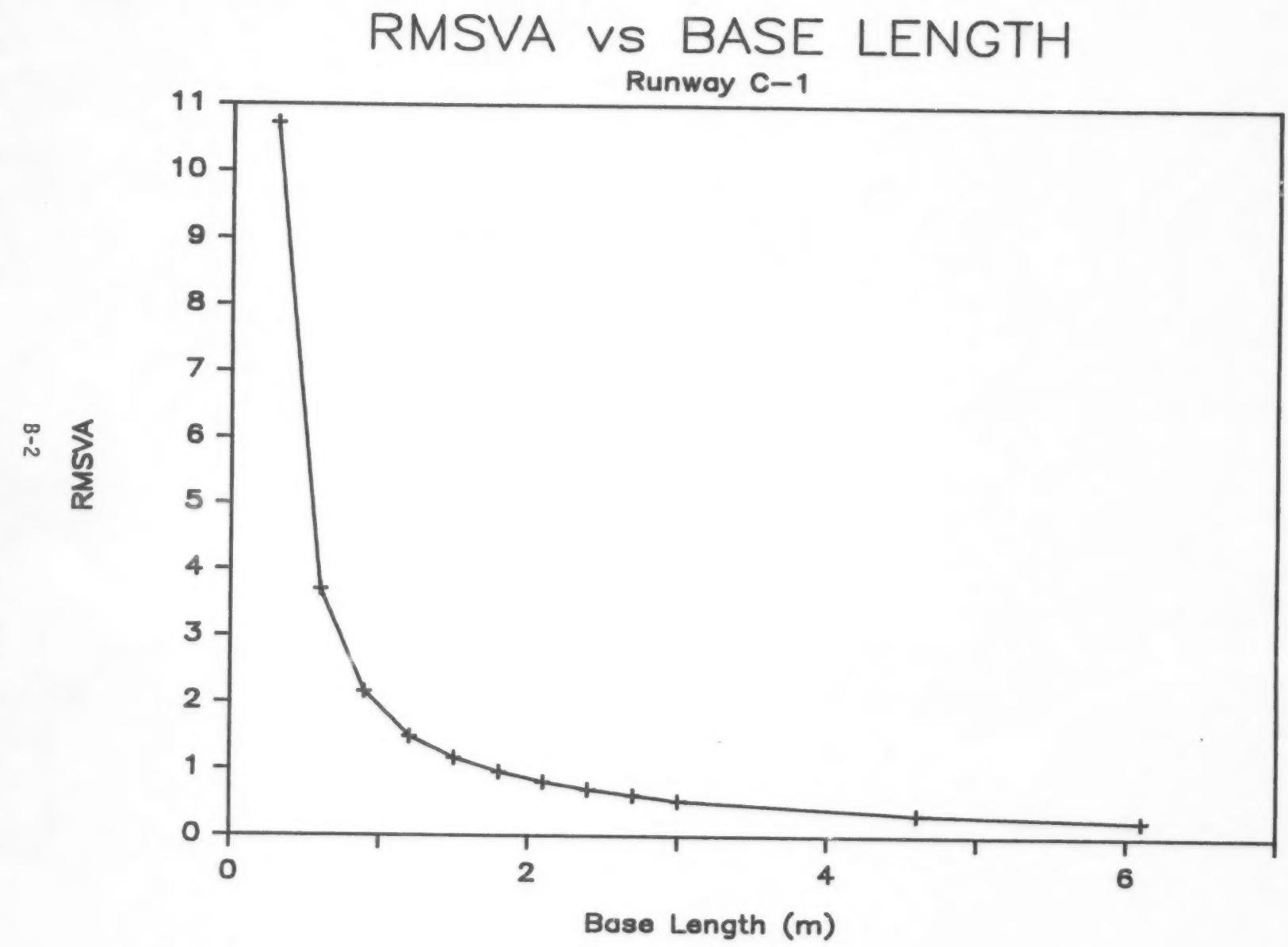


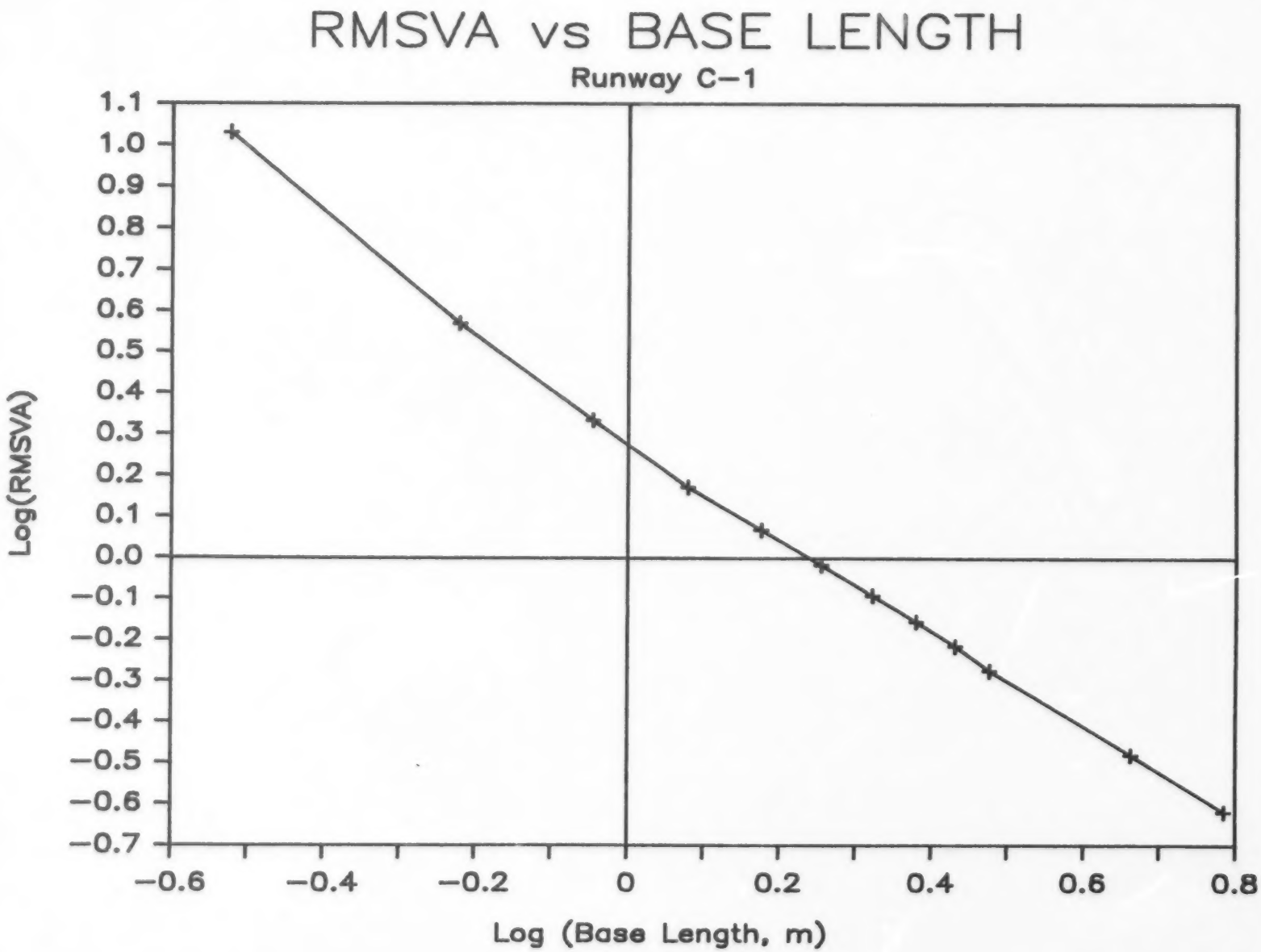
ROUGHNESS CORRELATION

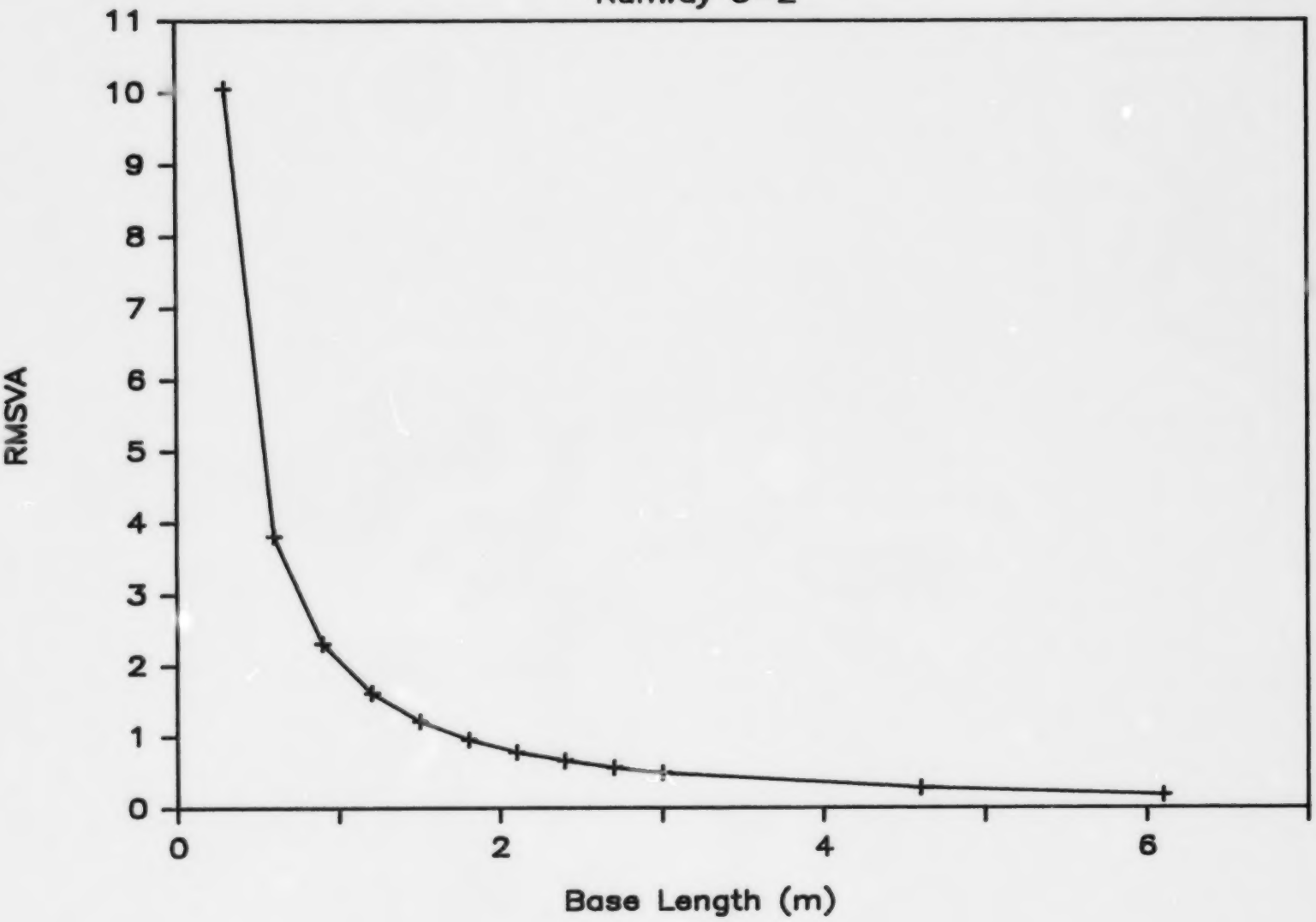


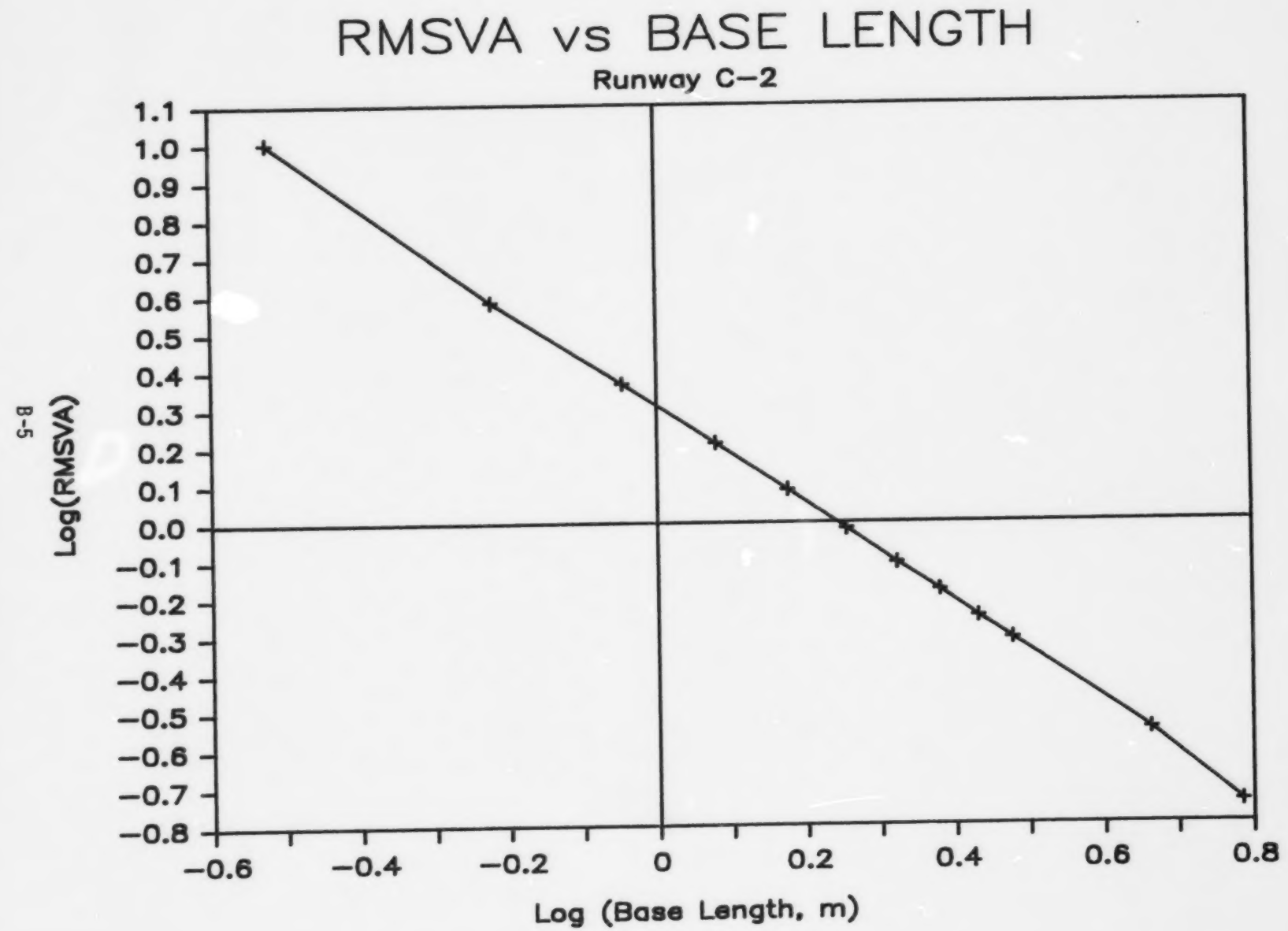
APPENDIX B

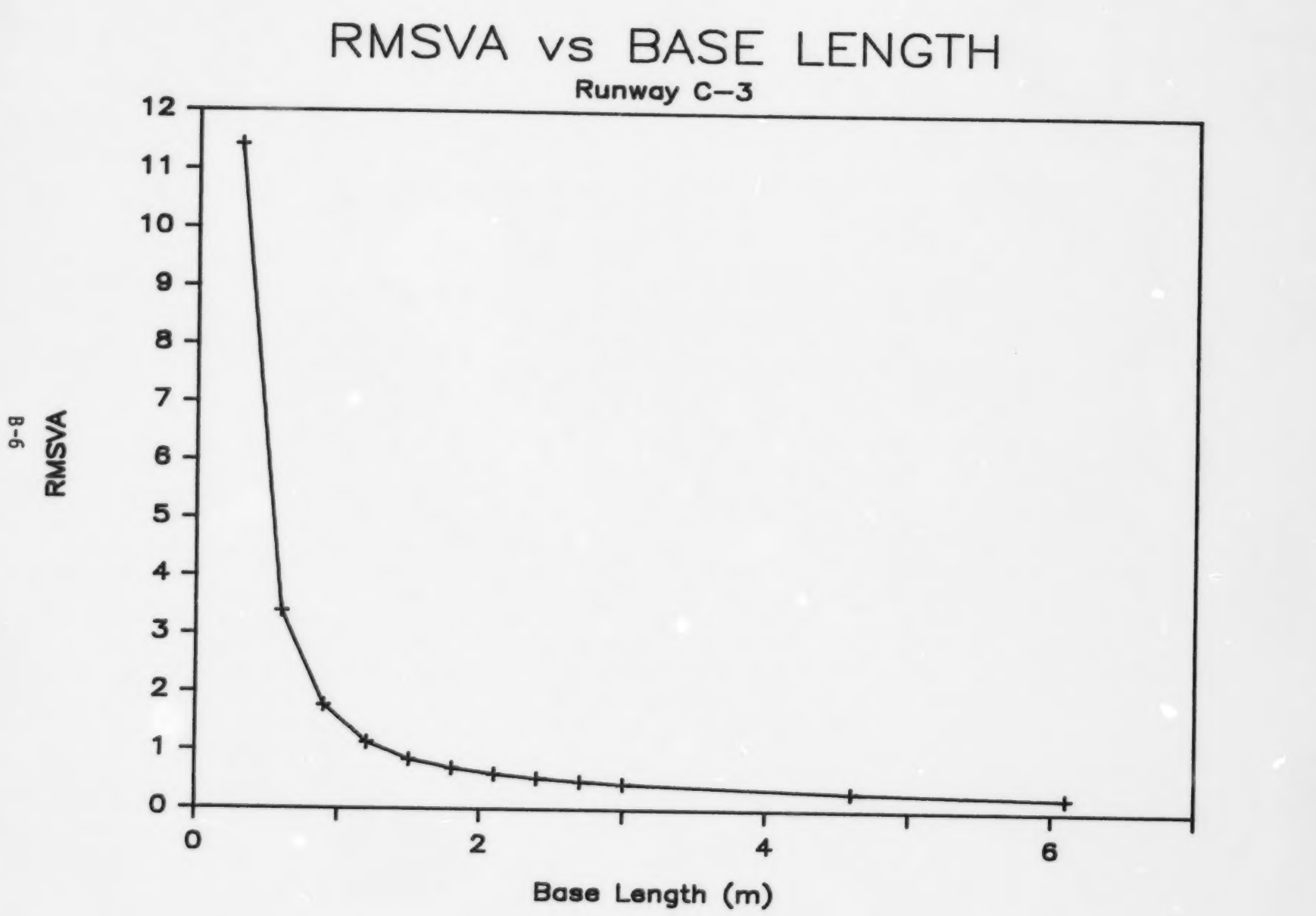
RMSVA versus Base Length Plots

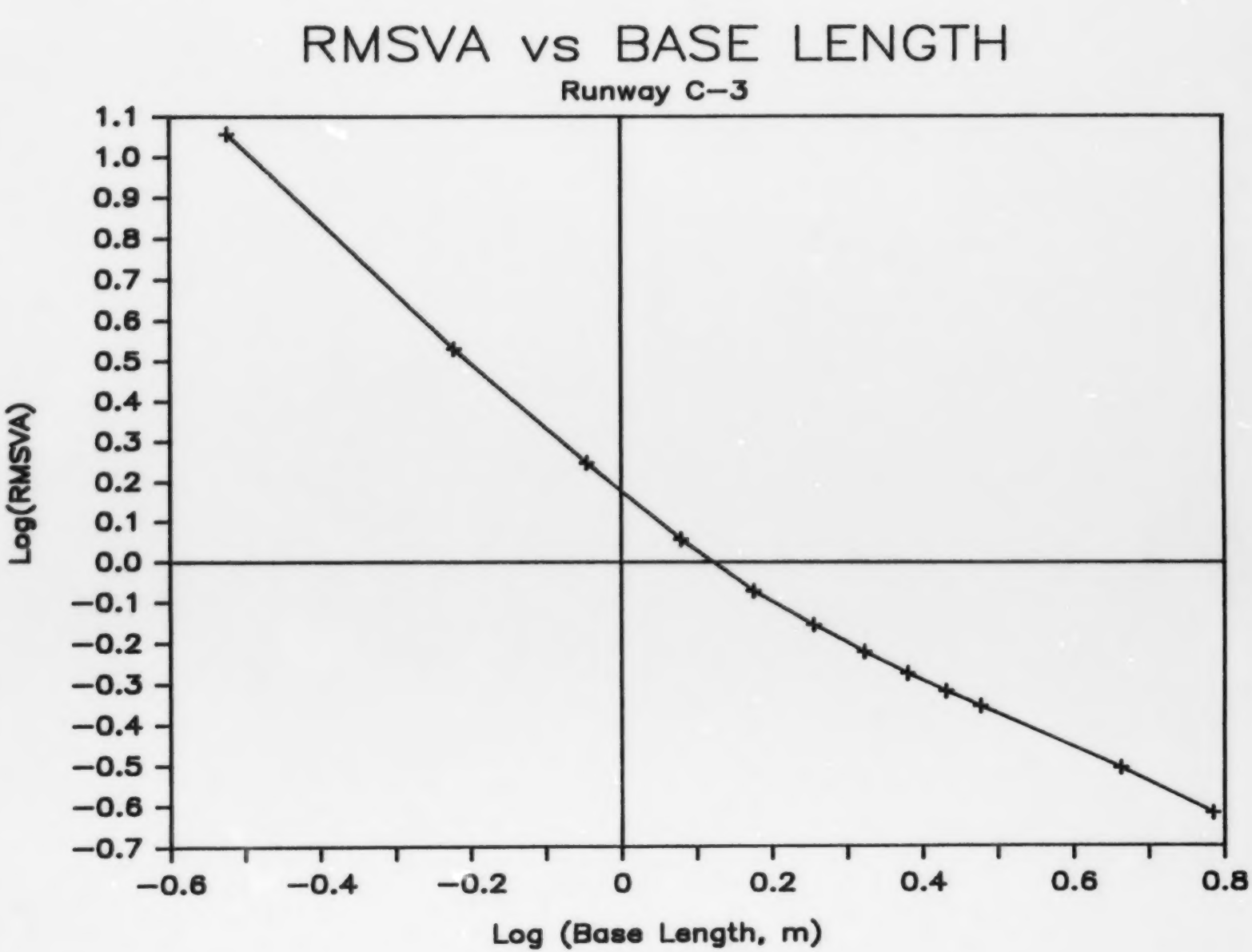

RMSVA vs BASE LENGTH
Runway C-1
RMSVA
11
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
Base Length (m)


RMSVA vs BASE LENGTH
Runway C-1
Log(RMSVA)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Log (Base Length, m)

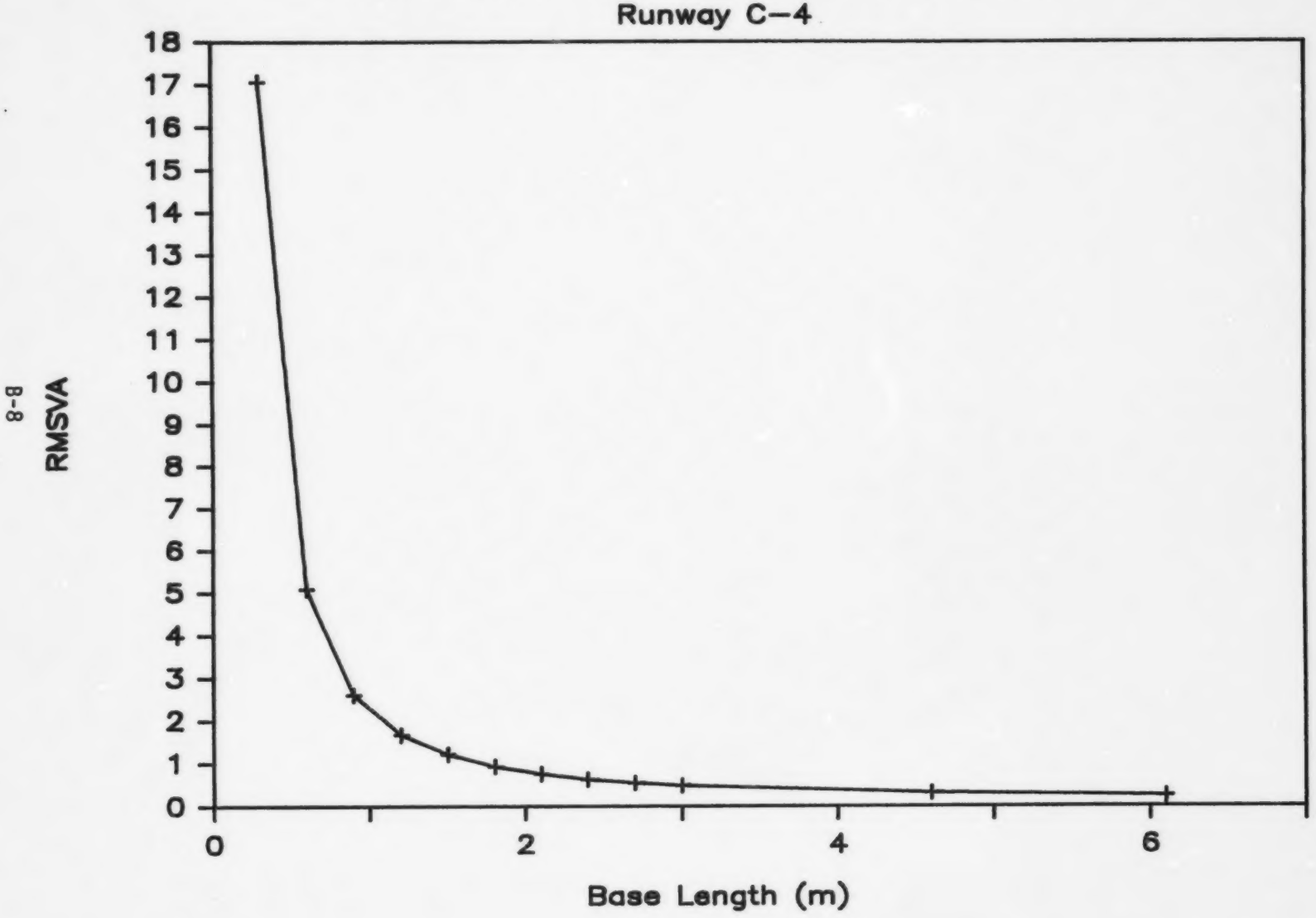

RMSVA vs BASE LENGTH
Runway C-2
RMSVA
Base Length (m)
0
1
2
3
4
5
6
7
8
9
10
11
0
2
4
6

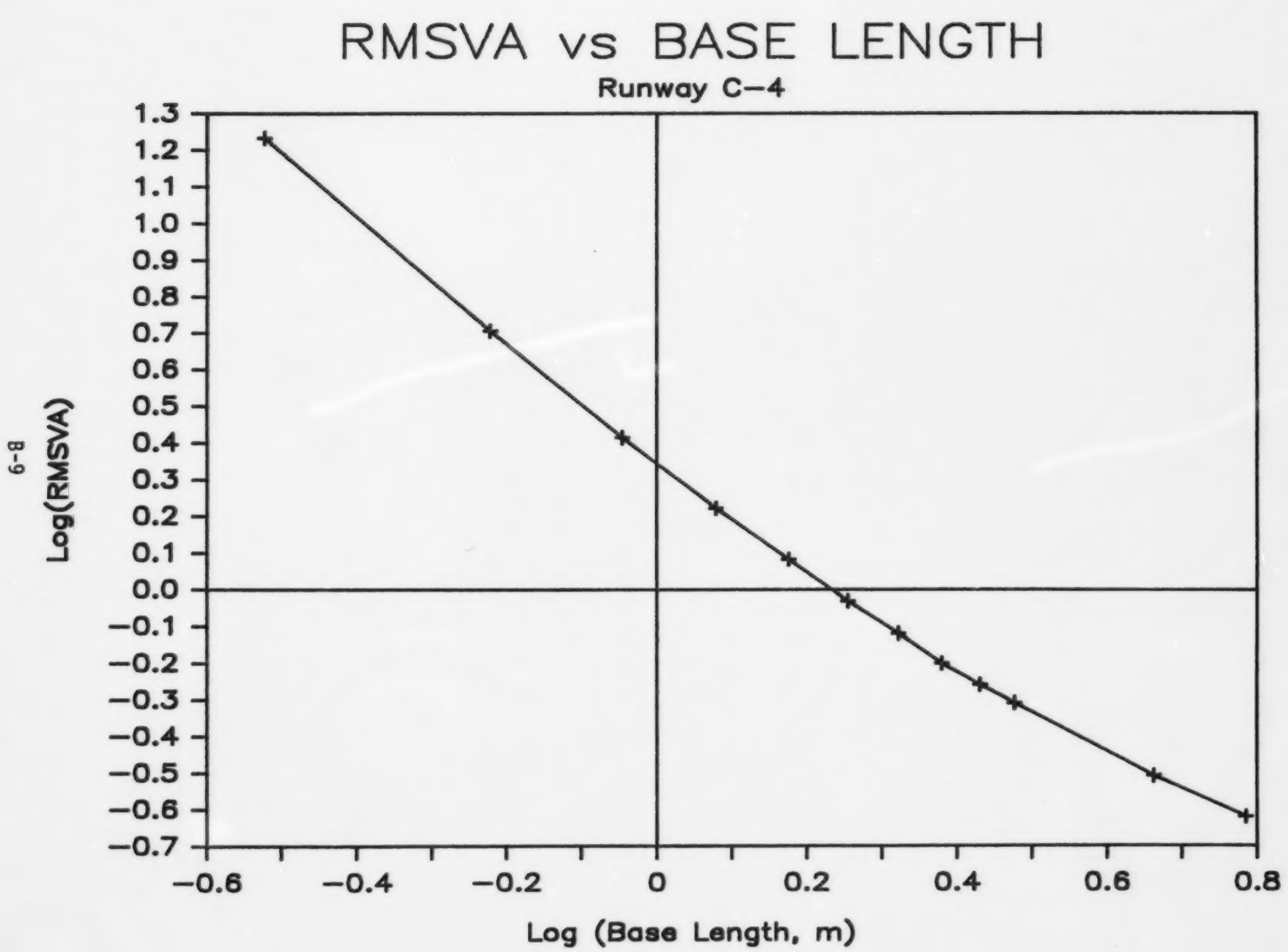

RMSVA vs BASE LENGTH
Runway C-2
Log(RMSVA)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Log (Base Length, m)


RMSVA vs BASE LENGTH
Runway C-3
RMSVA
12
11
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
Base Length (m)

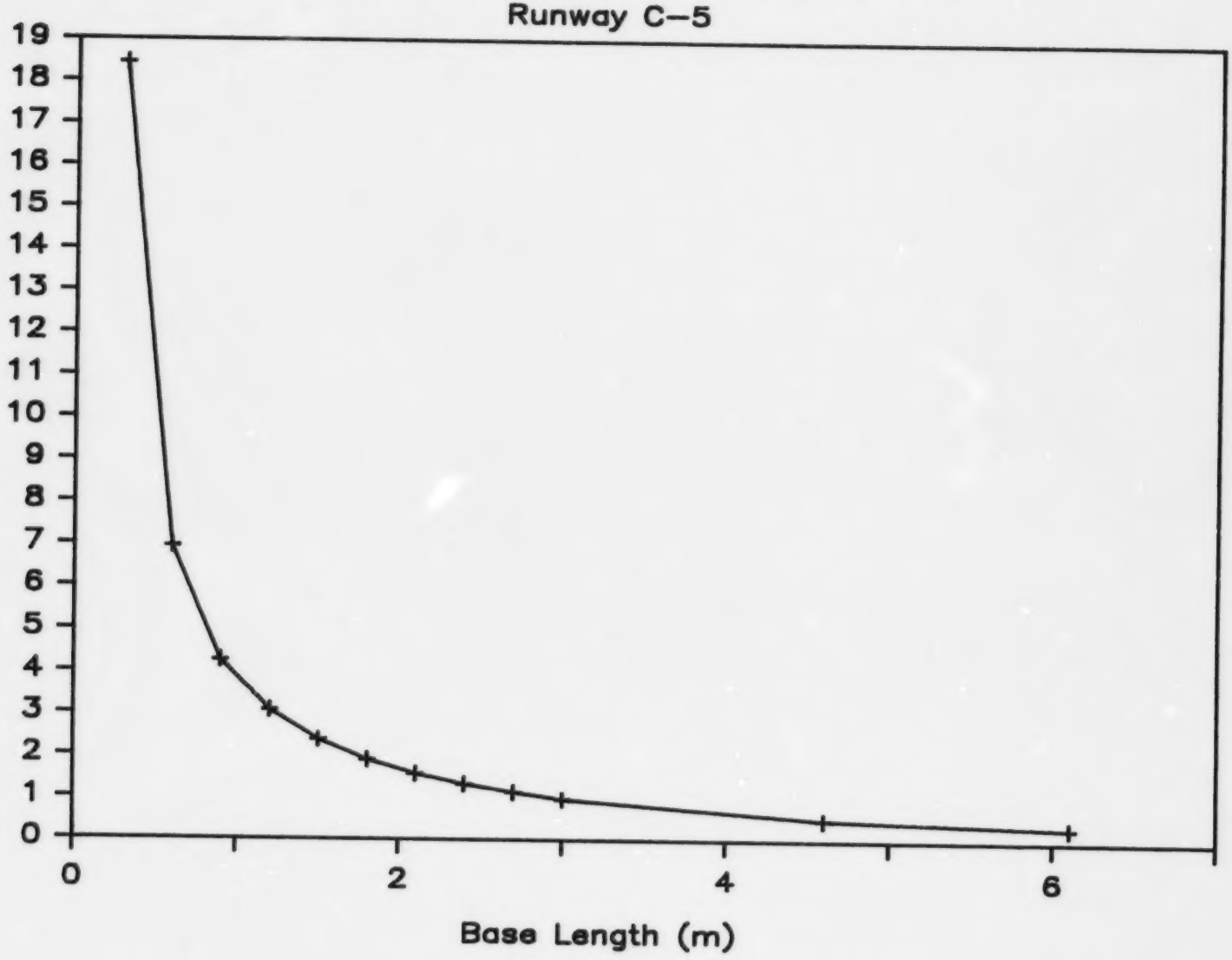

RMSVA vs BASE LENGTH
Runway C-3
Log(RMSVA)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Log (Base Length, m)

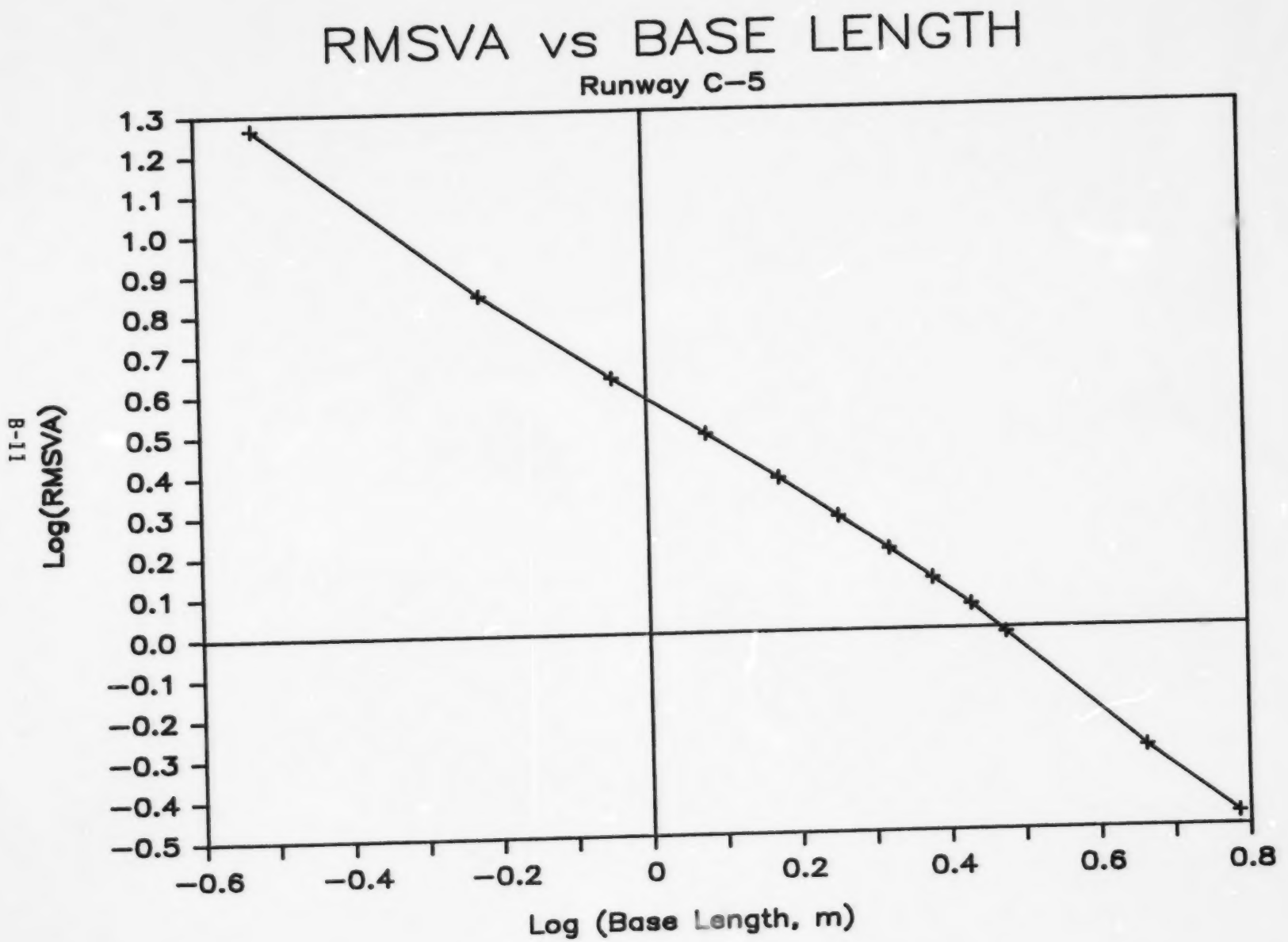
RMSVA vs BASE LENGTH

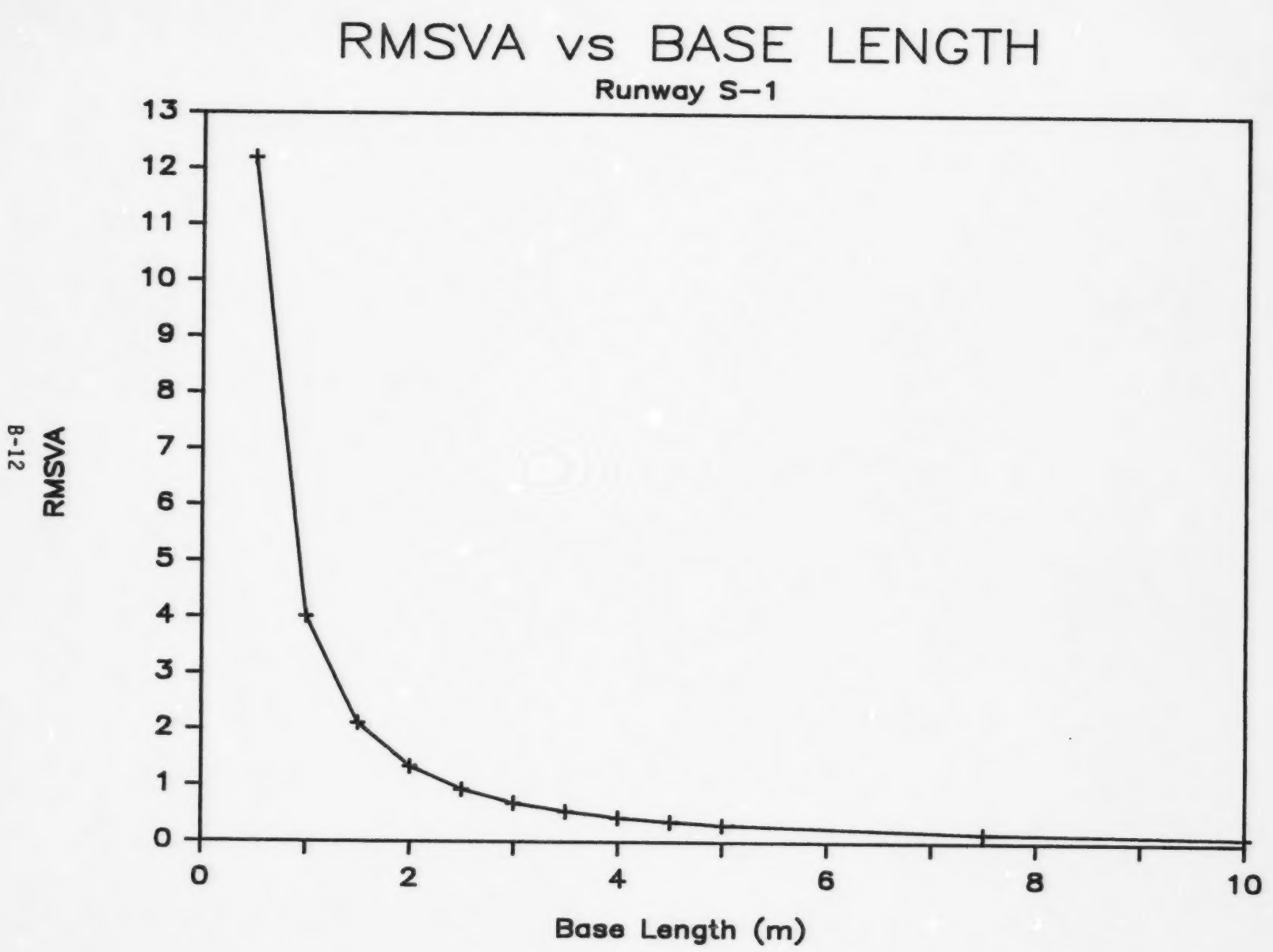


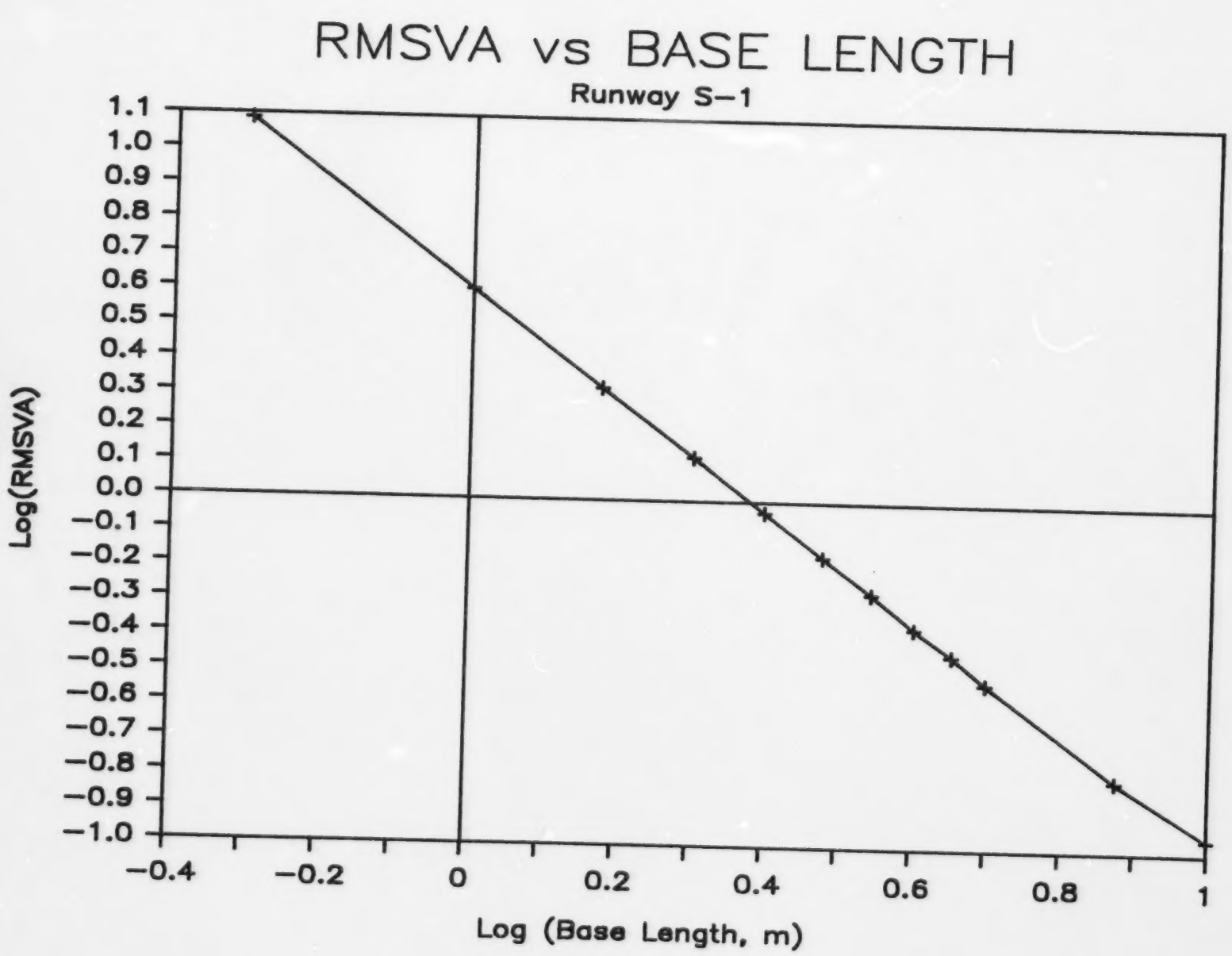

RMSVA vs BASE LENGTH
Runway C-4
Log(RMSVA)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
Log (Base Length, m)

RMSVA vs BASE LENGTH

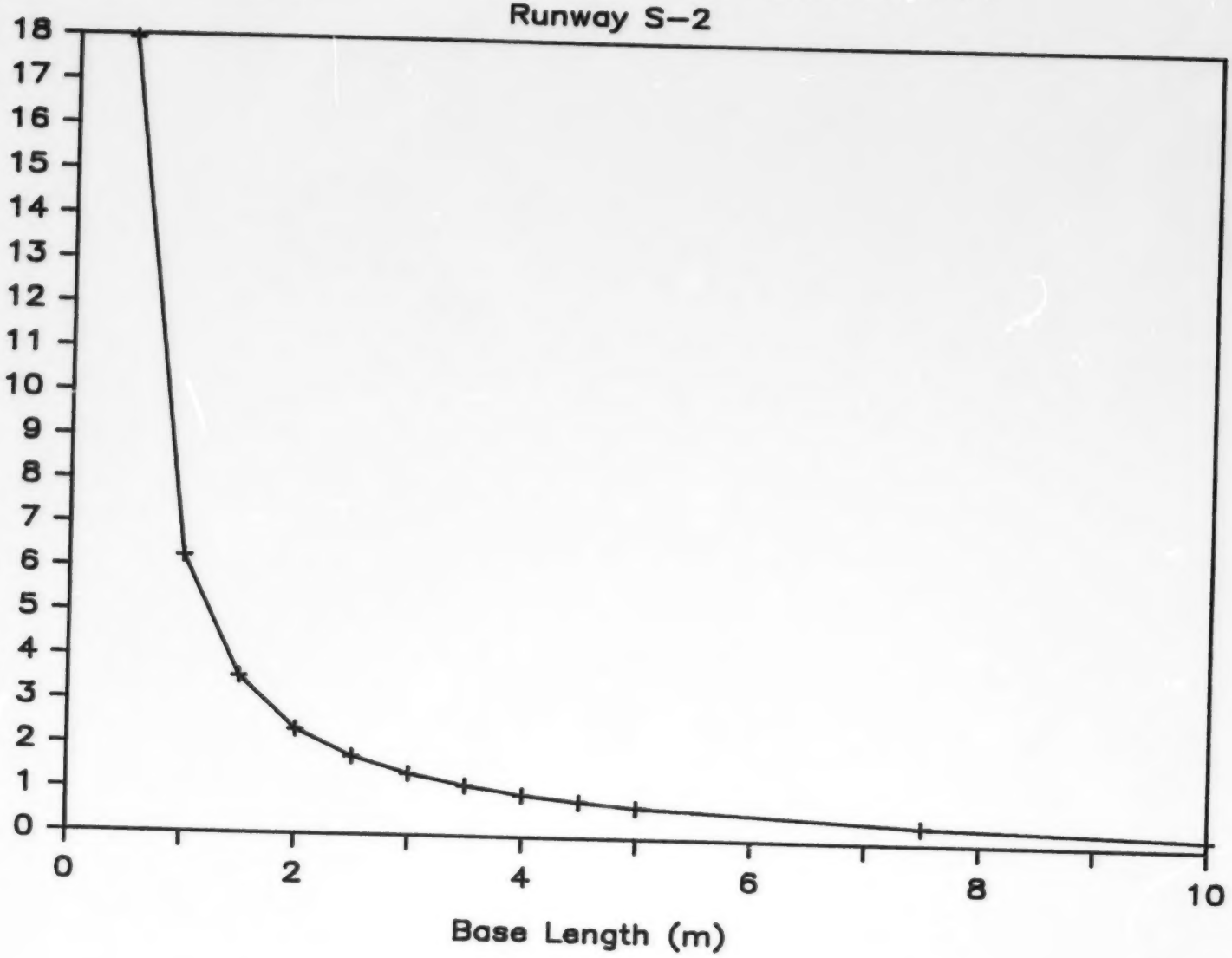


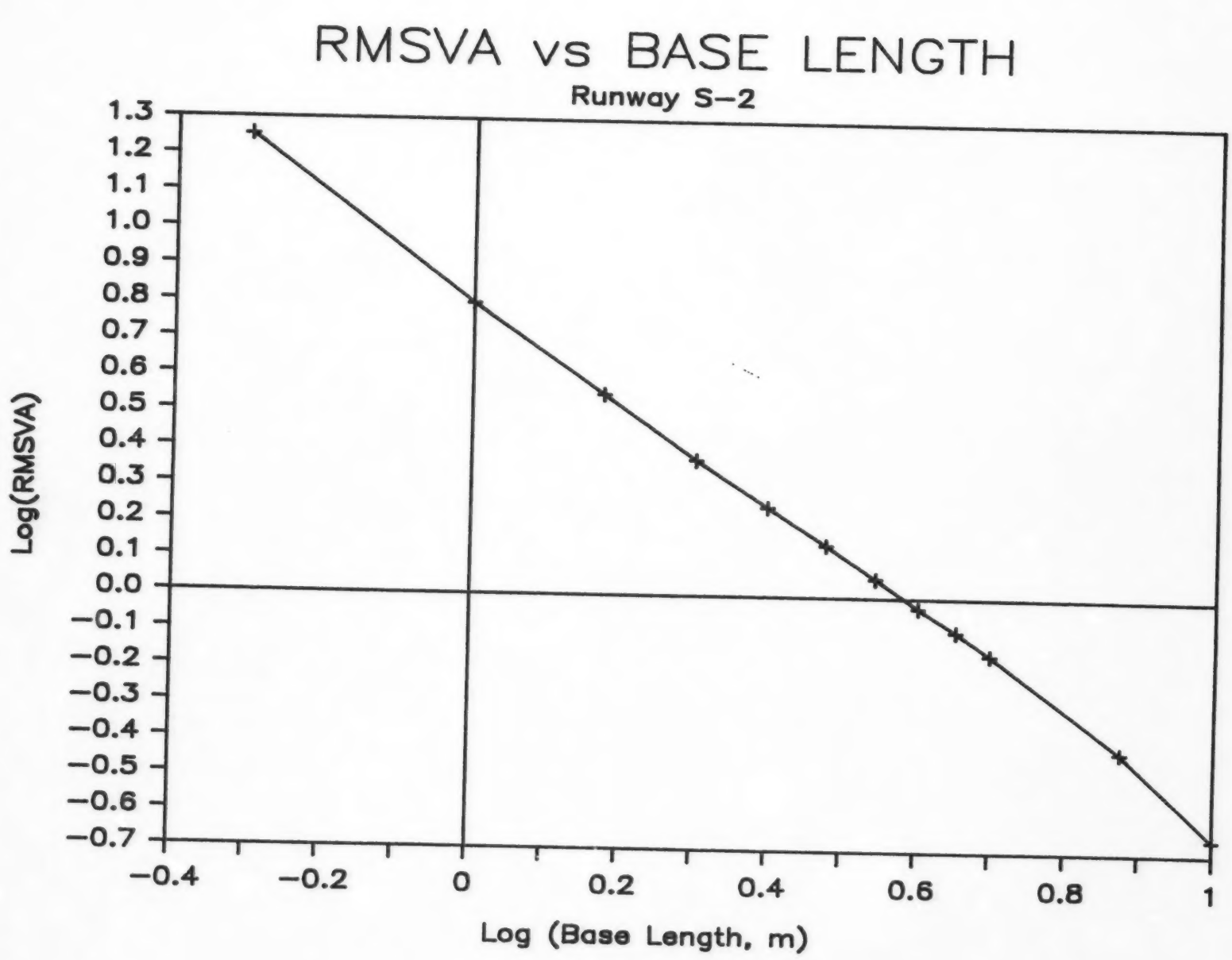

RMSVA vs BASE LENGTH
Runway C-5
Log(RMSVA)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Log (Base Length, m)

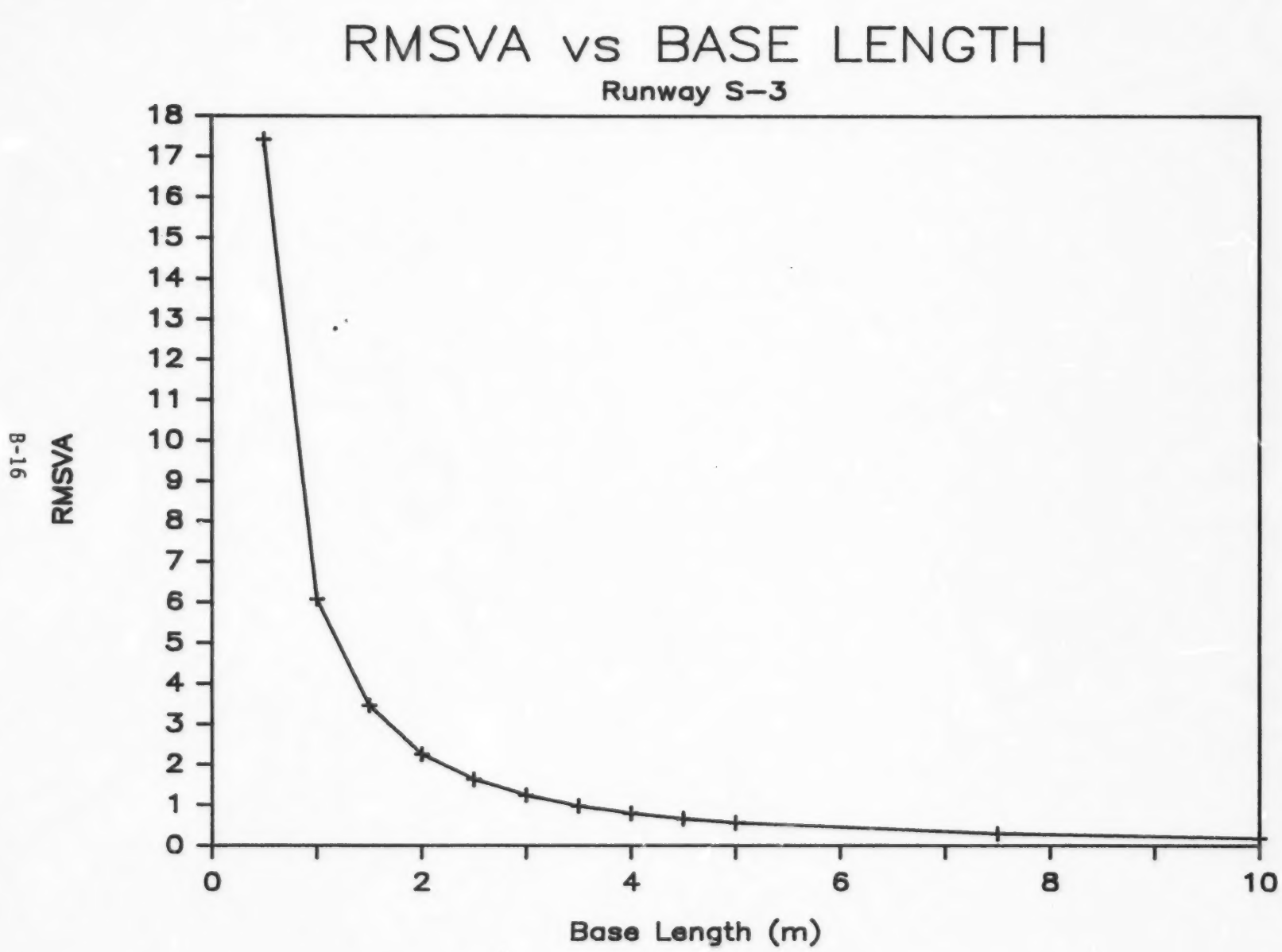

RMSVA vs BASE LENGTH
Runway S-1
RMSVA
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
Base Length (m)


RMSVA vs BASE LENGTH
Runway S-1
Log(RMSVA)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Log (Base Length, m)

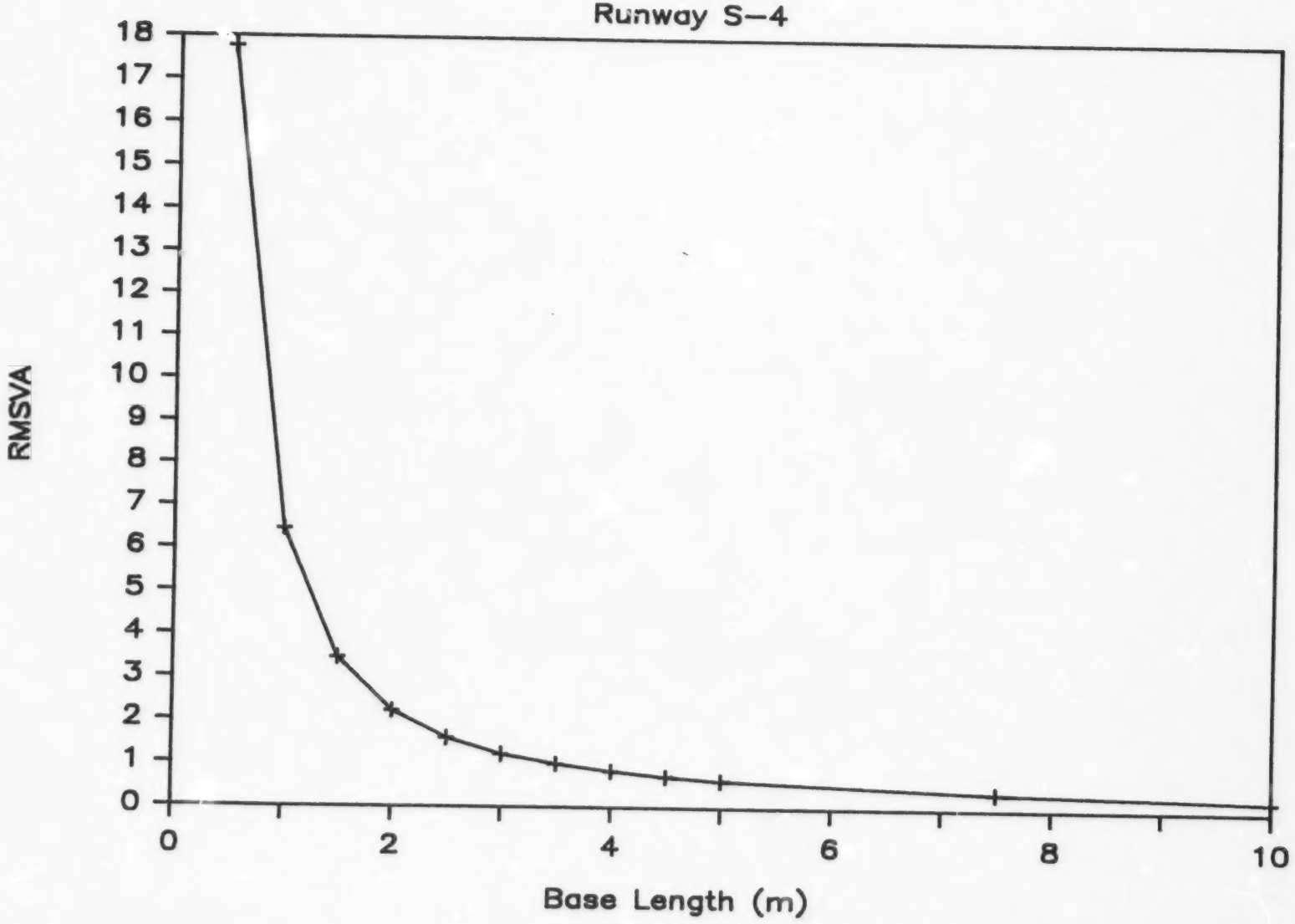
RMSVA vs BASE LENGTH

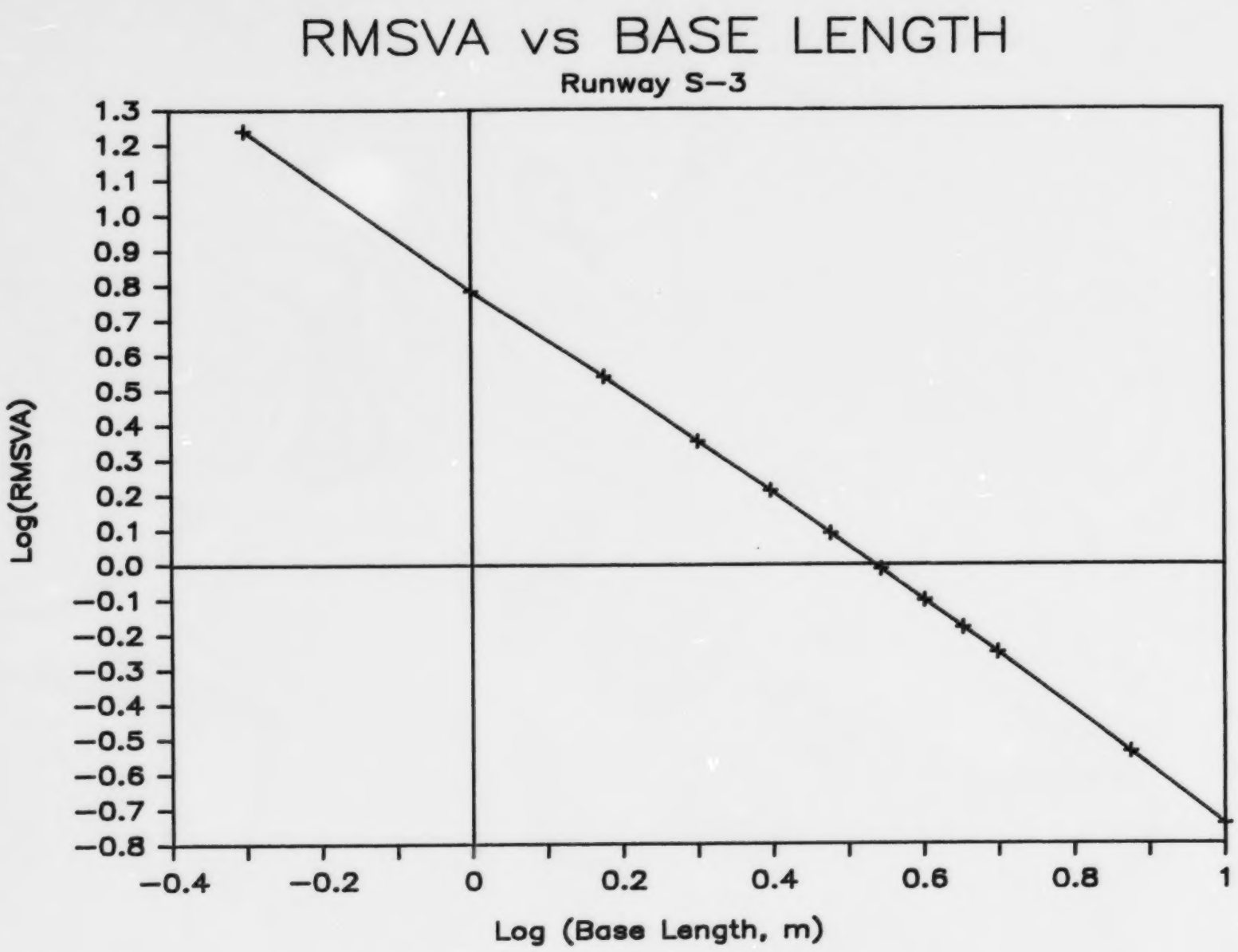



RMSVA vs BASE LENGTH
Runway S–2
Log(RMSVA)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Log (Base Length, m)


RMSVA vs BASE LENGTH
Runway S-3
RMSVA
Base Length (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
0
2
4
6
8
10

RMSVA vs BASE LENGTH




RMSVA vs BASE LENGTH
Runway S-3
Log(RMSVA)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Log (Base Length, m)

RMSVA vs BASE LENGTH